AgriEngineering

Article

Multi-Bale Handling Unit for Efficient Logistics

Robert "Bobby" Grisso [1,*], John Cundiff [1] and Kevin Comer [2]

1 Biological Systems Engineering, Virginia Tech, Blacksburg, VA 24061, USA; jcundiff@vt.edu
2 Antares Group Inc., Harrisonburg, VA 22801, USA; kcomer@antaresgroupinc.com
* Correspondence: rgrisso@vt.edu; Tel.: +1-540-231-1980

Received: 11 May 2020; Accepted: 12 June 2020; Published: 16 June 2020

Abstract: This paper presents a design for a feedstock logistics system to supply a bioenergy plant located in the Southeast USA, specifically Piedmont, a physiographic region covering part of five states (VA, NC, SC, GA, and AL). The design uses a perennial grass (switchgrass) as the feedstock. Harvest is done with a round baler, and round bales are stored in single-layer ambient storage in satellite storage locations. New technology, 20-bale racks, was designed as the multi-bale handling unit. The analysis shows how proper design of the interactions between the several unit operations in a "logistics chain" can be used to minimize average delivered cost for the feedstock required for 24/7 operation. Racks are loaded at the satellite storage and delivered by hauling contractors hired by the plant and controlled by a "Feedstock Manager" at the plant to insure approximately the same number of loads are received each day. Single-bale handling at the plant is eliminated, thus the truck unload time is reduced and truck productivity (tons/day) is increased. At-plant handling and storage in 20-bale racks increases plant receiving facility productivity, and gives a reduction in plant cost to supply a continuous steam of material for 24/7 operation.

Keywords: biomass; biomass logistics; hauling costs; in-field hauling; location allocation; management systems; satellite storage locations; transportation

1. Introduction

There is a belief that the feedstock logistics system for a bioenergy industry in one region can be replicated for a second region. While we agree that the logistics principles for any herbaceous biomass (cotton, sugar cane, and bioenergy) industry are the same, we believe that the *optimum* logistics system for each region will be unique. To illustrate that point, this paper gives a design for a bioenergy plant located in the Southeast USA, specifically the Piedmont, a physiographic region covering part of five states (VA, NC, SC, GA, and AL). The concept uses results from the literature to define a logistics system for a Piedmont plant that uses a perennial grass (switchgrass) as the feedstock.

The Piedmont is chosen because it is a physiographic region with adequate rainfall (≥40 inches annually) and much underutilized cropland. Some of this land is being converted back into forest for the woody biomass industry. The Southeast has two-thirds of the US paper mills and is considered to be a global "wood basket". Certain cropland can be converted into herbaceous biomass production without significant impact on food production.

The lowest average delivered cost for biomass used as a feedstock for bioenergy is achieved with an analysis that optimizes the key *interactions* between unit operations in the "logistics chain". In this study, new technology, 20-bale racks were designed as the multi-bale handling unit. The design analysis shows how the interactions between the several unit operations in a "logistics chain" can be used to minimize average delivered cost for the feedstock with a continuous stream of material for 24/7 operation, 47 weeks/year.

The key unit operations are defined as follows.

1. Harvesting—the several operations required to collect biomass into bales.
2. In-field hauling—the operation required to haul bales from the field and place them into a satellite storage location (SSL).
3. Highway hauling—the operations required to load bales at the SSL and haul them to the bioenergy plant.
4. Receiving facility—operations required to weigh a loaded truck, sample for quality parameters, unload, weigh the empty truck, and flow biomass into, and out of, at-plant storage as required for 24/7 operation.

The feedstock logistics system for a Piedmont plant is envisioned with a specific division of responsibilities. The first division is "farmgate operations", which includes production, harvest, "in-field hauling", and delivery to an SSL owned by the feedstock contract holder. The second division is "highway hauling", a commercial hauling contract written by the plant to transport biomass from the SSLs to the plant, and deliver a given number of loads per week for 47 weeks/year. The third division is the "receiving facility operations" and includes management of the feedstock at the plant, control of inventory, and control of the commercial hauler contract holders to insure a uniform delivery of biomass for year-round operation.

2. Review of Literature

2.1. Harvesting

Sokhansanj et al. [1,2] studied the entire biomass logistics system in a manner that linked the farmgate, highway hauling, and receiving facility operations. The study included round and square bales and stacks formed with chopped material in the field. The importance of understanding the linkage between various unit operations in the logistics chain was illustrated.

There is a very important interaction between the farmgate and highway hauling operations. The times that an SSL is filled and emptied impacts the storage cost to the SSL owner, as well as the operation of the hauling contractor. To orient the reader to the importance of the farmgate and highway hauling interaction, consider a baseline assumption that each SSL is filled at least twice annually. All parties would like to fill an SSL three times rather than two as this increases the amount of biomass stored per unit area of storage by 50%. Storage cost (USD/ton) for biomass stored in that SSL would be reduced by 50%. If the biorefinery contracts to have one SSL emptied three times per year and another only twice per year, the farmgate contract must include a higher storage fee for the SSL emptied only twice.

The equipment used for baling and in-field hauling is a critical issue to the farmgate contract holder. Farmers in the Southeastern USA are familiar with baling; thus, this specification allows the farmer to utilize conventional farm equipment for harvesting [3]. Utilizing currently owned equipment reduces capital investment cost to obtain a feedstock contract. The farmer's ability to use current equipment is a significant benefit, since harvesting/baling is the single most expensive component of switchgrass production [4]. More efficient harvest systems coupled with well-matched harvesting technologies specific to farm size and crop yield can minimize costs. For example, a study of switchgrass yields with delayed harvest until spring showed that switchgrass yields decreased almost 40% [5]. Nearly 10% of switchgrass yield reduction was due to a decrease in tiller mass; nearly 90% of switchgrass yield reduction was the result of biomass not recovered by the baler. A similar analysis of field studies also shows similar findings, suggesting the need for improvement of baler equipment efficiency to retain yields over the harvest season [1]. To emphasize the need for well-matched harvesting technologies that are farm and crop specific, an Alabama study examined the time required to mow, rake, and bale high and low yields of switchgrass with commercial equipment [6]. Conclusions were high yield crops had the greatest difficulties during baling. High yield fields and the smaller baler required more time to complete a bale due to equipment downtime resulting from a jammed baler. Bransby et al. [6]

did not address the unrecovered biomass from the baler; however, they did emphasize the need for switchgrass harvesting and bailing equipment research.

Large round and square balers are two well-known and widely accessible harvesting technologies [7], which offer a range of advantages and disadvantages to farmgate operations. Round bales have the ability to shed water, which reduces the need for costly storage options and offers the maximum number of harvest days [8]. Square bales offer the added benefit of greater bulk density, ease of transport, and increased machine productivity. However, the increased capital investment for the baler and the larger tractor required, as well as the square bale's inability to shed water, lessen its potential on many farms.

Moisture causes damage and loss of dry matter in switchgrass bale storage. Dry matter storage losses in switchgrass bales, display a general trend to be greater from outside bale storage compared to inside bale storage [9–11]. Furthermore, dry matter storage losses are far greater for covered square bales than uncovered round bales [11]. They showed large uncovered round bales had a better economic return than covered square bales, when considering the cost incurred due to biomass storages losses. However, Chariton Valley RC&D [4] advocates the use of square baling and highlights successful case use using square bales, due to the handling-hauling advantage.

2.2. *Highway Hauling*

Continuing the discussion of the farmgate and the highway hauling operations, the square bale logistical advantage is observed during highway hauling. Highway hauling is constrained by the legal dimensions of the truck. The density of round bales is too low to achieve the load-legal mass per truckload. As stated, the square bale offers a greater bulk density when compared to the round bale.

Several researchers have studied biomass-biofuel supply chain in order to optimize the ideal location, size, and number of bio-refineries as well as biomass delivery over multiple periods. Zhu and Yao [12] considered multiple feedstocks in a logistics model and determined the optimal locations for warehouses, harvest machinery numbers, and biomass deliveries.

An et al. [13] developed a multi-seasonal model for the biomass-biofuel supply chain reaching from biomass producers to markets. An and Wilhelm [14] considered several different feedstocks and postulated a solution method for large-scale supply chains more effectively. Lin et al. [15] optimized the number locations and capacities of processing plants and the amount of biomass produced, transported, and stored of Miscanthus from fields to ethanol markets. Xie et al. [16] incorporated several transport modes including truck, single railcar, and whole train to optimize the supply chain aiming to minimize costs.

2.3. *Centralized Control*

Most complex logistics chains are organized with central control. A study specific to corn stover in the Midwest (large rectangular bales) was done by Aguayo et al. [17] and Aguayo et al. [18], and a study specific to switchgrass in the Piedmont (round bales, rack system) was done by Judd et al. [19]. In each study, the productivity of the system of equipment was enhanced (in tons/week) using central control. Neither study considered the receiving facility cost to achieve the needed continuous flow of material for 24/7 operation, so any cost benefit was not reported.

2.4. *Satellite Storage Locations*

Studies analyzed the impact of bio-refinery size on the average delivered cost for the collection of sparsely distributed biomass. These studies showed that the size of a centralized bio-refinery has a significant impact on logistics cost [20,21]. Other studies examined the tradeoff between transport costs and facility costs of a de-centralized bio-refineries [22–24]. In these studies, biomass harvested from fields were stored at SSLs and then transported to the final destination.

Further studies examined the long-distance transport of biomass and the most appropriate locations and number of SSLs. For example, Yu et al. [25] determined the optimal number of SSLs and their locations using GIS, as well as best bio-refinery location. Igathinathane et al. [26] analyzed the location of biomass bales and field exits to minimize in-field logistics. Similarly, Subhashree et al. [27] assessed bale storage locations within field areas and concluded that the field midpoint (based on field dimensions) was the most efficient.

Economic feasibility has been evaluated by estimating the costs to deliver biomass to a bio-refinery [28–33]. Sultana and Kumar [34] estimated the delivery cost of different biomass packages. An and Searcy [35] proposed an improved logistics system using large packages of biomass. Grisso et al. [36] compared four harvest scenarios and calculated the number of harvest machines and available storage capacity. They concluded that using SSLs is more cost-effective than using centralized storage. Gonzales et al. [37] analyzed the high-volume and long-distance transport of densified biomass. Lu et al. [38] assessed costs for energy consumption and greenhouse gas emissions from road, railway, and waterway transport. Golecha et al. [39] developed an equation set to estimate costs from fields to a centrally located bio-refinery that considered yield density and tortuosity factors.

Some studies considered the impact of moving of loaders between SSLs. Ravula et al. [40] modeled these movements using the traveling salesman problem. They assumed that the loader works at an SSL for a minimal period (e.g., several days) and will be transported to another SSL overnight or on a workday. An [41] developed a model to minimize the total cost of transporting biomass from SSLs to a bio-refinery. He considered multiple trips and visits and synchronized loading operations at SSLs. This study concludes that transporting biomass using an on-site loader at the most distant SSLs may provide the most economical use of transport machines. They estimated the transportation cost at 8.88–9.50 USD per dry Mg. Similar concepts were investigated by others [17–19,42]. These authors suggested that a smaller SSLs (in storage volume) may be more desirable when compared larger SSLs, due to the low cost of moving the loaders.

3. Feedstock Logistics Design—Piedmont Plant

3.1. Harvesting

Harvesting is the most weather dependent unit operation; thus, it is imperative that " ... *the logistics chain be organized such that the harvesting operation is never delayed*". Every day that the crop conditions (maturity and moisture content) and field conditions (traffic ability for equipment) are satisfactory must be a harvest day. The harvest must never be slowed due to a delay in any other unit operation.

A classic example of the "never delay the harvest" principle is the cotton industry. This industry is transitioning from modules to bales because the harvesting machine, cotton harvester, has limited on-board storage. An in-field hauling unit, quaintly named a boll buggy, must arrive on time to receive the dumped seed cotton for harvest to proceed. The boll buggies cycle between the harvester and a module builder located at the edge of the field, where the seed cotton is compacted into modules. These modules, 20-ft long blocks of compacted seed cotton, are covered and hauled with special self-loading trucks. With a well-run module system, the harvester is "on the row" about 70% of a harvest day.

The new system uses a harvester that bales the seed cotton in round bales 7 ft diameter × 8 ft long and covers them with solid plastic, not net. It does not stop to wrap a bale. There is a chamber where a new bale is being formed, while the current bale is being wrapped and ejected. These bales can be hauled later, thus *uncoupling* the harvest and in-field hauling operations (Figure 1).

There are three benefits of the cotton baling system. The authors list them in their perceived importance, highest first.

1. The harvester's time on the row is increased from 70% to 90%—higher tons/day capacity.
2. The *uncoupling* of the harvest and in-field hauling operation increases the efficiency of in-field hauling-fewer delays means higher tons/day capacity per unit of equipment.

3. The round bales are hauled on standard flat-bed trailers; a special truck (module hauler) is not needed. However, a forklift, or a tractor with front-end loader large enough to handle the bales, is needed.

In the bioenergy industry, as with the cotton industry (also an herbaceous biomass industry), baling uncouples the harvesting and in-field hauling operations, thus it provides an important benefit. Forage chopping requires that an in-field hauling unit (truck or wagon) be beside the harvester for the harvest to continue. Any delay in the cycling of the in-field hauling units reduces the harvester operating time, and thus its daily capacity. Baling provides for maximum capacity (in tons/day) of the harvesting machine, a very important advantage.

Since this study focuses on a region of high rainfall, round bales (specifically 5 ft diameter × 4 ft long round bales) were chosen. This bale configuration is hereafter referred to as 5 × 4 bales. The round bale, because the rounded top sheds rainfall, can be left in the field and hauled the next day, or even the following week. The capacity of the in-field hauling equipment need not equal the capacity of the harvester, since extra time is available for in-field hauling.

The reader can immediately recognize a key interaction with later unit operations in the logistics chain, specifically the highway hauling of round bales. The round bale was developed to harvest hay to be fed on the farm where it was produced. Can a solution be found to offset this major disadvantage?

Figure 1. Round baling of cotton.

3.2. In-Field Hauling

The machine envisioned for in-field hauling is a self-loading, self-propelled bale wagon which unloads by tilting the bed and allowing the bales to roll off into single-layer storage (Figure 2). The envisioned wagon will haul 10, 5 × 4 bales. A machine with similar specifications was built by New Holland over 35 years ago. It did not find sufficient market to be a commercial success, thus it is no longer available. However, other in-field hauling options for round bales are currently available.

The Piedmont is characterized by relatively small irregular-shaped fields over rolling terrain, thus an SSL might store biomass from several fields, as compared to the Midwest, with larger fields, where a road-side storage would typically store material from a single field. A simple analysis showed that the in-field hauling operator can have the same labor productivity (in tons/h) as the baling operator if the ton-mile parameter is less than 2. The ton-mile parameter is defined by summing the product of the distance hauled times the mass of each load stored in an SSL and dividing this sum by the total tonnage stored. A value of 2 means that, on average, each ton was hauled two miles.

The proposed plan for the Southeast envisions maximum opportunity for small- and intermediate-sized farmers to get a feedstock contract. Most of these farmers cannot justify the investment in specialized in-field hauling equipment required. It is expected that an owner of this equipment will obtain additional in-field hauling contracts to accumulate the annual hours required for cost-effective operation of the equipment. This option is practical because the hauling of round bales from the field can be done some time after baling is completed—*the operations are uncoupled*.

Figure 2. Concept for in-field hauling with self-propelled, self-loading bale wagon.

3.3. Highway Hauling

Truck productivity (in tons hauled/day) is constrained by the travel speed and load volume (height, width, and length) set by highway regulations. The two parameters that most affect cycle time (time to load truck, travel to bioenergy plant, unload, and return) are the load and unload times. The most cost-effective truck operation will be achieved when the logistics chain is organized to minimize load and unload time.

The concept for a rack system to haul round bales was first introduced by Cundiff and Grisso [8], and has been subsequently analyzed, as summarized in the Review of Literature. A prototype rack and trailer were designed and built (Figure 3) using funding from DOE Project "BALES", and some preliminary testing has been done. A truckload is defined as two trailers each carrying a 20-bale rack (Figure 4).

Figure 3. Prototype 20-bale rack and trailer designed and built by Sea Box, East Riverton, NJ (note the pintle hook hitch).

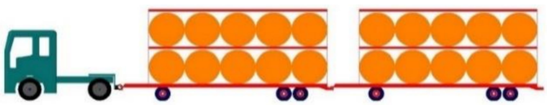

Figure 4. Concept showing two 20-bale racks to form one truckload.

A simple example can show the influence of truck load and unload time. Loads of round bales, two racks with 20 bales each, were assumed to be:

$$\frac{0.3825 \text{ dry tons}}{\text{bale}} \times \frac{40 \text{ bale}}{\text{load}} = 15.3 \text{ dry tons/load} \tag{1}$$

Truck cycle time is calculated as follows. A database for a 30-mi radius of Greta, VA was created with "perspective" biomass production fields identified from aerial photography. The average travel distance over existing roads for biomass delivered from SSLs to a bioenergy plant was 25.4 mi. Using the average haul of 25.4 mi and the average speed over rural roads of 45 mi/h, the travel time one way is 0.56 h, or 33 min. Travel time for a round trip is 66 min. If the time to load 40 bales is 45 min (very ambitious), and unload time (weigh in, sample, unload, and weigh out at the plant) averages 45 min (also very ambitious), total cycle time is (45 + 2 × 33 + 45 =) 156 min, or 2.6 h.

Theoretical average number of loads in a 12-h haul day is 4.61 loads/day. We assumed that the achieved truck capacity in a production situation will average 66% of theoretical, or (4.61 × 0.66 =) 3 loads/day. The assumed truck cost (truck tractor to pull two trailers) is 458.65 USD/day for a 12-h workday, which includes ownership plus operating cost (including labor but excluding fuel). The receiving facility is assumed to be open 12 h/day, thus the hauling "day" is 12 h. Truck cost, accounting for one operator for a 12-h haul day, excluding fuel, is:

$$\frac{\frac{458.65 \text{ USD}}{\text{day}}}{3\frac{\text{loads}}{\text{day}} \times 15.3 \text{ dry}\frac{\text{tons}}{\text{load}}} = \frac{9.99 \text{ USD}}{\text{dry tons}} \sim \frac{10 \text{ USD}}{\text{dry tons}} \tag{2}$$

3.3.1. Truck Fuel Cost

Round trip distance is 50.8 mi. Fuel efficiency for short-haul operations, using current truck designs, is typically about 6 mi/gal, thus the fuel consumption per load is (50.8 mi ÷ 6 mi/gal) = 8.47 gal. At a fuel cost of 3.00 USD/gal (0.79 USD/liter), the fuel cost per load is (8.47 gal × 3.00 USD/gal) = 25.41 USD. Fuel cost per dry ton is (25.41 USD/load ÷ 15.3 dry tons/load) = 1.66 USD/dry tons.

Total Truck Cost (45 min load, 45 min unload):

$$\begin{aligned} \text{Ownership and operating} + \text{ Fuel } &= \text{ Total} \\ 10.00 + 1.66 &= 11.66 \text{ USD / dry tons} \end{aligned} \tag{3}$$

If the time to load 40 bales is 10 min (as shown below), and unload time averages 10 min, total cycle time is (10 + 2 × 33 + 10) = 86 min, or 1.43 h. Theoretical average number of loads in a 12-h haul day is (12 h ÷ 1.43 h/load =) 8.39 loads/day. We assumed that the achieved truck capacity in a production situation will average 60% of theoretical, or (8.39 loads/day × 0.60) = 5 loads/day. Truck cost, accounting for one operator, excluding fuel, is:

$$\frac{\mathbf{458.65 \text{ USD/day}}}{\mathbf{5\frac{loads}{day} \times 15.3 \text{ dry}\frac{tons}{load}}} = \frac{\mathbf{6.00 \text{ USD}}}{\mathbf{dry\ tons}} \tag{4}$$

Total Truck Cost (10 min load, 10 min unload):

$$\begin{aligned} \text{Ownership and operating} + \text{ Fuel } &= \text{ Total} \\ 6.00 + 1.66 &= 7.66 \text{ USD / dry tons} \end{aligned} \tag{5}$$

Truck cost is reduced from 11.66 to 7.66 USD/dry tons, or 34%, if the load/unload times can be reduced from 45 to 10 min.

3.3.2. Load Time

It is clear that a 10-min load time cannot be achieved with single-bale loading while the truck waits. Thus, the option chosen is the uncoupling of the loading and hauling operations. The racks are filled on the trailers at the SSL. When the truck arrives, two empty trailers are dropped, and the two loaded trailers hauled away. The expected exchange time (backup camera in the truck, pintle hook hitch) is 10 min, thus the 10 min load time criteria can be achieved. Tandem trailers are legal in all 50 states, and performance data from the commercial trucking industry verifies that a two-trailer tandem can be unhooked from the truck tractor and a new tandem hooked in less than 5 min.

3.3.3. Unload Time

It is clear that a 10-min unload time cannot be achieved with single-bale unloading while the truck waits. To unload the truck, a forklift lifts off the two full racks and replaces them with two empty racks. This unload method emulates the bin system used by a sugar mill to minimize truck unload time (Figure 5). Typical time to unload a truck, three bins with two on the main trailer and one on a "pup" trailer, is 3 min. No one in the timber industry unloads a log truck one log at a time (Figure 6), and no one with a cost-effective herbaceous biomass logistics chain will unload one bale at a time.

Figure 5. Bin system used for rapid unloading of sugar cane at a sugar mill.

Figure 6. Unload operation for log trucks at a paper mill.

3.4. Receiving Facility

The design and operation of the receiving facility at the bioenergy plant is critical to meeting the 10-min unload time target. Obviously, the most efficient operation can be achieved when approximately the same number of trucks arrive each hour during the day. This requires central control of the trucking.

3.4.1. Central Control of Feedstock Delivery

The industry will operate most efficiently when the load-haul companies are under contract to the bioenergy plant. We propose the following organization. The plant will own the racks and trailers. The load-haul company will own the equipment (telehandlers and service trucks) to load racks at the SSL and the truck tractors to pull the loads. A "Feedstock Manager" at the plant will be the hub of the information network. Information (when a load is ready) will flow from the SSL to the Feedstock Manager over the cellular network. In addition, the feedstock manager will get real-time data from GPS units in each truck and have cellular network contact with the operator. The feedstock manager will instruct truck operators when to deliver and will coordinate receiving facility operations.

3.4.2. Rack Unloading

The bales arrive at the bioenergy plant in the rack, which gives 20 bales in a defined orientation. Every load has the same orientation. This is an important operational benefit which can be used to reduce cost. The key is no single bale handling at the receiving facility.

Prototype testing of a "rack unloader" has been conducted by Sea Box, East Riverton, NJ. The rack has four compartments with five bales each. The rack unloader shifts the rack to align a compartment with the exit conveyor. Then, a ram pushes the five bales onto a conveyor (Figure 7). This procedure is repeated to empty the other three compartments, thus establishing a line of 20 bales on the conveyor to be fed individually to a horizontal mill. A Vermeer mill can currently process 5 × 4 round bales of corn stover at a maximum rate of one bale every 45 s. Keeping the conveyor charged with bales to achieve this productivity is a challenge. Currently, the design goal for a production rack unloader is a machine which can average one rack unloaded every 20 min and do this reliably for 24/7 operation. More development is needed.

Figure 7. Prototype rack unloader designed and developed by Sea Box to unload racks.

3.4.3. Rapid Truck Unloading

Operations at the receiving facility define average unload time for the trucks. The 10-min unload time target does not include time spent waiting in a queue. It is understood that some delays are unavoidable, and these delays will increase the average unload time for the truck fleet.

The following criteria will improve the delivery operations.

Weighing the truck—this is commercial technology widely used by a number of industries and by weigh stations on highways. In the case of multiple vendors delivering with their own trucks, the driver will swipe a card at a reader station just prior to pulling on the scale. The identity and weight are recorded for billing purposes.

In the case of loads of round bales from multiple SSLs, we envision that each rack will have a bar code plate mounted is a slot on the front corner. This bar code plate will be installed at the SSL when the rack is loaded. When the truck drives onto the scale, the bar code will be read automatically thus identifying the owner of the biomass for entry, along with the weight, into a database. This will automate the payment process.

Quality sampling—a near infrared reflection (NIR) probe has been developed which provides the potential for rapid collection of needed quality information. The probe is pressed into a bale in the radial direction using a small hydraulic cylinder, and the readings are made as it is pulled out (Figure 8).

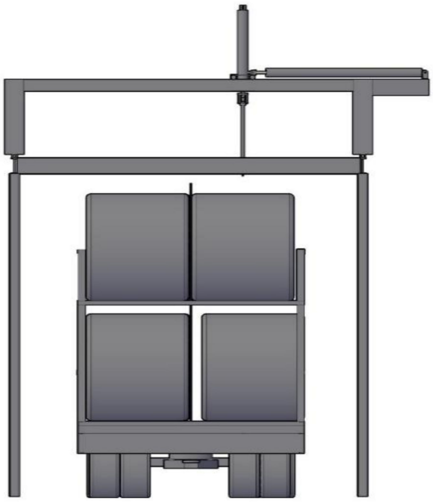

Figure 8. Near infrared reflection (NIR) probe inserted in bale to collect quality.

A beam travels to control the position of the probe and is mounted above the scale (Figure 9). When the truck stops at the control point on the scale, the beam travels to automatically sample three bales selected at random by the sampling software. This procedure emulates the current commercial practical; other options are available.

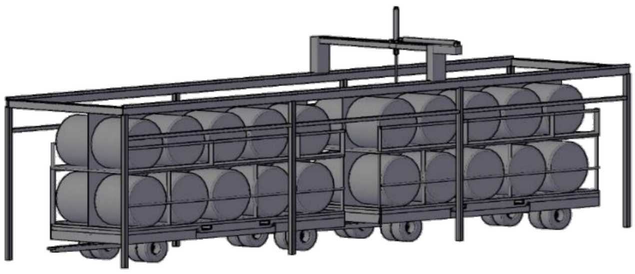

Figure 9. Traveling beam used to automatically select bales for sampling.

The bales in the bottom two compartments, defined as the bottom tier, are not sampled. Is this a significant disadvantage? Remember that the rack loading is done by a company under contract to the bioenergy plant. They are instructed to load bales at random, thus there should be no bias to load all low-quality bales on the bottom tier.

Unloading racks from truck—this operation is done thousands of times per day in the handling of shipping containers. The racks are designed with equivalent lift points and twist locks to attach to the trailer currently used in the shipping container industry. When removed from the truck, a rack can be placed immediately into the rack unloader, or it will be stacked two-high in at-plant storage.

Stored racks will be processed during times when deliveries are not being received. It is emphasized that the logistics chain must supply a continuous stream of feedstock for 24/7 operation.

3.4.4. At-Plant Storage

We postulate that it is a significant advantage to have 20-bale handling units in at-plant storage, as compared to individual bales. This is a new concept for the current bioenergy industry, but it is commercial practice for other industries.

The concept of "containerized" storage at the plant is used by the sugar industry. In past commercial practice, this industry used bins that are about the same size as the racks discussed in this study. Much of the cotton industry uses modules that are about the same size as the bins in the sugar industry. These modules are placed in at-plant storage and ginned during times when no deliveries are being received. Bins, modules, and racks are all examples of containerized storage at the plant.

Sugar cane, once it is chopped into billets during the harvest operation, must be processed within 12 h. A sugar mill operates 24/7 during the 140-day season when sugar cane is processed. Bins stored two-high in at-plant storage are removed as needed to supply the mill for nighttime operation (Figure 10). The next day, bins emptied during the night are loaded onto trucks for return to the field (Figure 11).

Figure 10. Full bin being placed in at-plant storage for later use for nighttime operation.

Figure 11. Empty bin being removed from storage and loaded onto truck for return to field.

The cost of the racks is a key consideration for the rack system. The rack system does considerably reduce the cost of forklift operations to flow material into and out of at-plant storage, a huge issue, particularly in inclement weather. Anyone considering the rack system will do a cost comparison to see if a higher cost for one-unit operation in the logistics chain will be more than offset by a lower cost for another unit operation, thus giving a reduced average cost for a continuous stream of biomass into their plant.

The first question is: What is the cost of the racks? With knowledge of the average number of loads/rack/week, a rack cost per dry ton was computed [43]. The cost of the racks, when all at-plant storage is rack storage, is 5.25 USD/dry tons. Is this a reasonable investment considering the benefit gained? As shown above, reducing load/unload time from 45 to 10 min would reduce truck cost from 11.66 to 7.66 USD/dry tons, a reduction of 4.00 USD/dry tons. Savings in forklift operating cost to flow material into and out of at-plant storage has not been defined. It is hoped that future work will include a complete cost analysis.

4. Conclusions—Design Specifications

The following design specifications were developed for a feedstock logistics system to supply a Piedmont plant for 24/7 operations, 47 weeks/year.

Round bales (5 ft diameter × 4 ft long) were chosen. These bales can be baled with equipment commonly available on small- and intermediate-sized farms, thus their specification encourages a higher density of feedstock contracts within a given radius of the plant, which minimizes average hauling distance. In addition, these bales can be stored in single layer ambient storage, the lowest cost storage option.

Satellite storage is owned by the feedstock contract holder, and the feedstock contract includes a storage fee. Computation of this fee will be the most complex feature of the contract.

The multi-bale handling unit designed is a 20-bale rack. A significant advantage is gained when single-bale handling is eliminated at the plant. In addition, an advantage is gained when at-plant storage is in 20-bale racks. Racks and trailers will be owned by the plant.

The plant will contract with hauling companies to load racks at the satellite storage and deliver a given number of loads per week for 47 weeks/year operation. Centralized control of trucking is essential to minimize delays, maximize truck productivity, and thus minimize truck cost (USD/dry tons). Of equal importance, it maximizes receiving facility productivity, and thus minimizes receiving facility cost.

Author Contributions: Conceptualization, R.B.G., J.C., and K.C.; Methodology, J.C., and K.C.; Writing—Original Draft Preparation, J.C.; Writing—Review and Editing, R.B.G.; Investigation, R.B.G.; and Project Administration, K.C., and J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

References

1. Sokhansanj, S.; Turholow, A.F.; Stephen, J.; Stumborg, M.; Fenton, J.; Mani, S. Analysis of five simulated straw harvest scenarios. *Can. Biosys. Eng.* **2008**, *50*, 2.27–2.35.
2. Sokhansanj, S.; Turhollow, A.F.; Wilkerson, E.G. *Development of the Integrated Biomass Supply Analysis and Logistics Model (IBSAL)*; Technical Memorandum ORNL/TM-2006/57; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2008.
3. Jensen, K.; Clark, C.; Ellis, P.; English, B.; Menard, J.; Walsh, M.; De la Torre Ugarte, D. Farmer willingness to grow switchgrass for energy production. *Biomass Bioenergy* **2007**, *31*, 773–781. [CrossRef]
4. Chariton Valley, R.C.D. *Chariton Valley Biomass Project—Draft Fuel Supply Plan*; Contract Number: DE-FC36-96GO10148; United States Department of Energy: Washington, DC, USA, 2002.
5. Adler, P.R.; Sanderson, M.S.; Boateng, A.A.; Weimer, P.J.; Jung, H.J.G. Biomass yield and biofuel quality of switchgrass harvested in fall or spring. *Agron. J.* **2006**, *98*, 1518–1525. [CrossRef]
6. Bransby, D.I.; Sladden, S.E.; Downing, M. Yield effects on bale density and time required for commercial harvesting and baling of switchgrass. In Proceedings of the BIOENERGY '96—The Seventh National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies, Nashville, TN, USA, 15–20 September 1996.
7. Reynolds, S.G.; Frame, J. *Grasslands: Developments, Opportunities, Perspectives*; CRC Press, Science Publ. Inc: Enfield, NH, USA, 2005; p. 556.
8. Cundiff, J.S.; Grisso, R.D. Containerized handling to minimize hauling cost of herbaceous biomass. *Biomass Bioenergy* **2008**, *32*, 308–313. [CrossRef]
9. Sanderson, M.A.; Egg, R.P.; Wiselogel, A.E. Biomass losses during harvest and storage of switchgrass. *Biomass Bioenergy* **1997**, *12*, 107–114. [CrossRef]
10. Shinners, K.J.; Boettcher, G.C.; Muck, R.E.; Wiemer, P.J.; Casler, M.D. Harvest and storage of two perennial grasses as biomass feedstocks. *Trans. ASABE* **2010**, *53*, 359–370. [CrossRef]

11. Larson, J.A.; Mooney, D.F.; English, B.C.; Tyler, D.D. Cost Analysis of Alternative Harvest and Storage Methods for Switchgrass in the Southeastern USA. In Proceedings of the Annual Meeting of Southern Agricultural Economics Association, Orlando, FL, USA, 6–9 February 2010.
12. Zhu, X.; Yao, Q. Logistics system design for biomass-to-bioenergy industry with multiple types of feedstocks. *Bioresour. Technol.* **2011**, *102*, 10936–10945. [CrossRef]
13. An, H.; Wilhelm, W.E.; Searcy, S.W. A mathematical model to design a lignocellulosic biofuel supply chain system with a case study based on a region in Central Texas. *Bioresour. Technol.* **2011**, *102*, 7860–7870. [CrossRef]
14. An, H.; Wilhelm, W.E. An exact solution approach based on column generation and a partial-objective constraint to design a cellulosic biofuel supply chain. *Comput. Chem. Eng.* **2014**, *71*, 11–23. [CrossRef]
15. Lin, T.; Rodríguez, L.F.; Shastri, Y.N.; Hansen, A.C.; Ting, K.C. Integrated strategic and tactical biomass-biofuel supply chain optimization. *Bioresour. Technol.* **2014**, *156*, 256–266. [CrossRef]
16. Xie, F.; Huang, Y.; Eksioglu, S. Integrating multimodal transport into cellulosic biofuel supply chain design under feedstock seasonality with a case study based on California. *Bioresour. Technol.* **2014**, *152*, 15–23. [CrossRef] [PubMed]
17. Aguayo, M.M.; Sarin, S.C.; Cundiff, J.S.; Comer, K.; Clark, T. A corn-stover harvest scheduling problem arising in cellulosic ethanol production. *Biomass Bioenergy* **2017**, *107*, 102–112. [CrossRef]
18. Aguayo, M.M.; Sarin, S.C.; Cundiff, J.S. A branch-and-price approach for a biomass feedstock logistics supply chain design problem. *IISE Trans.* **2019**, *51*, 1348–1364. [CrossRef]
19. Judd, J.D.; Sarin, S.C.; Cundiff, J.S. Design, modeling, and analysis of a feedstock logistics system. *Bioresour. Technol.* **2012**, *113*, 209–218. [CrossRef] [PubMed]
20. Leboreiro, J.; Hilaly, A.K. Biomass transportation model and optimum plant size for the production of ethanol. *Bioresour. Technol.* **2011**, *102*, 2712–2723. [CrossRef]
21. Wang, Y.; Ebadian, M.; Sokhansanj, S.; Webb, E.; Lau, A. Impact of the biorefinery size on the logistics of corn stover supply—A scenario analysis. *Appl. Energy* **2017**, *198*, 360–376. [CrossRef]
22. Lamers, P.; Roni, M.S.; Tumuluru, J.S.; Jacobson, J.J.; Cafferty, K.G.; Hansen, J.K.; Kenney, K.; Teymouri, F.; Bals, B. Techno-economic analysis of decentralized biomass processing depots. *Bioresour. Technol.* **2015**, *194*, 205–213. [CrossRef]
23. Kim, S.; Dale, B.E. Comparing alternative cellulosic biomass biorefining systems: Centralized versus distributed processing systems. *Biomass Bioenergy* **2015**, *74*, 135–147. [CrossRef]
24. Kim, J.; Realff, M.J.; Lee, J.H.; Whittaker, C.; Furtner, L. Design of biomass processing network for biofuel production using an MILP model. *Biomass Bioenergy* **2011**, *35*, 853–871. [CrossRef]
25. Yu, H.; Wang, Q.; Ileleji, K.E.; Yu, C.; Luo, Z.; Cen, K.; Gore, J. Design and analysis of geography distribution of biomass power plant and satellite storages in China. Part 2: Road delivery. *Biomass Bioenergy* **2012**, *46*, 785–792. [CrossRef]
26. Igathinathane, C.; Tumuluru, J.S.; Keshwani, D.; Schmer, M.; Archer, D.; Liebig, M.; Halvorson, J.; Hendrickson, J.; Kronberg, S. Biomass bale stack and field outlet locations assessment for efficient in field logistics. *Biomass Bioenergy* **2016**, *91*, 217–226. [CrossRef]
27. Subhashree, S.N.; Igathinathane, C.; Bora, G.C.; Ripplinger, D.; Backer, L. Optimized location of biomass bales stack for efficient logistics. *Biomass Bioenergy* **2017**, *96*, 130–141. [CrossRef]
28. Berry, M.D.; Sessions, J. The economics of biomass logistics and conversion facility mobility: An Oregon case study. *Appl. Eng. Ag.* **2018**, *34*, 57–72. [CrossRef]
29. Caputo, A.C.; Palumbo, M.; Pelagagge, P.M.; Scacchia, F. Economics of biomass energy utilization in combustion and gasification plants: Effects of logistic variables. *Biomass Bioenergy* **2005**, *28*, 35–51. [CrossRef]
30. Cameron, J.B.; Kumar, A.; Flynn, P.C. The impact of feedstock cost on technology selection and optimum size. *Biomass Bioenergy* **2007**, *31*, 137–144. [CrossRef]
31. Kumar, A.; Cameron, J.B.; Flynn, P.C. Biomass power cost and optimum plant size in western Canada. *Biomass Bioenergy* **2003**, *24*, 445–464. [CrossRef]
32. Larson, E.D.; Marrison, C.I. Economic scales for first-generation biomass-gasifier/gas turbine combined cycles fueled from energy plantations. *J. Eng. Gas. Turbines Power* **1997**, *119*, 285–290. [CrossRef]
33. Wolfsmayr, U.J.; Rauch, P. The primary forest fuel supply chain: A literature review. *Biomass Bioenergy* **2014**, *60*, 203–221. [CrossRef]

34. Sultana, A.; Kumar, A. Optimal configuration and combination of multiple lignocellulosic biomass feedstocks delivery to a biorefinery. *Bioresour. Technol.* **2011**, *102*, 9947–9956. [CrossRef]
35. An, H.; Searcy, S.W. Economic and energy evaluation of a logistics system based on biomass modules. *Biomass Bioenergy* **2012**, *46*, 190–202. [CrossRef]
36. Grisso, R.D.; McCullough, D.; Cundiff, J.S.; Judd, J.D. Harvest schedule to fill storage for year-round delivery of grasses to biorefinery. *Biomass Bioenergy* **2013**, *55*, 331–338. [CrossRef]
37. Gonzales, D.; Searcy, E.; Ekşioĝlu, S.D. Cost analysis for high-volume and long-haul transportation of densified biomass feedstock. *Transp. Res. Part. A Policy Pract.* **2013**, *49*, 48–61. [CrossRef]
38. Lu, X.; Withers, M.R.; Seifkar, N.; Field, R.P.; Barrett, S.R.H.; Herzog, H.J. Biomass logistics analysis for large scale biofuel production: Case study of loblolly pine and switchgrass. *Bioresour. Technol.* **2015**, *183*, 1–9. [CrossRef] [PubMed]
39. Golecha, R.; Gan, J. Biomass transport cost from field to conversion facility when biomass yield density and road network vary with transport radius. *Appl. Energy* **2016**, *164*, 321–331. [CrossRef]
40. Ravula, P.P.; Grisso, R.D.; Cundiff, J.S. Comparison between two policy strategies for scheduling trucks in a biomass logistic system. *Bioresour. Technol.* **2008**, *99*, 5710–5721. [CrossRef]
41. An, H. Optimal daily scheduling of mobile machines to transport cellulosic biomass from satellite storage locations to a bioenergy plant. *Appl. Energy* **2019**, *236*, 231–243. [CrossRef]
42. Cundiff, J.S.; Grisso, R.D. In-field operations to deliver biomass to a biorefinery. *Agric. Eng. Int. CIGR J.* **2012**, *14*, 5–22.
43. Grisso, R.D.; Cundiff, J.S.; Comer, K. Why a multi-bale handling unit is essential for efficient feedstock logistics. In Proceedings of the ASABE Annual International Meeting, Boston, MA, USA, 7–10 July 2019; ASABE Paper No. 1900802.