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Development and implementation of integrated biomass supply analysis and logistics model (IBSAL)

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Abstract

This paper describes the framework development of a dynamic integrated biomass supply analysis and logistics model (IBSAL) to simulate the collection, storage, and transport operations for supplying agricultural biomass to a biorefinery. The model consists of time dependent events representing the working rate of equipment and queues representing the capacity of storage structures. The discrete event and queues are inter-connected to represent the entire network of material flow from field to a biorefinery. Weather conditions including rain and snow influence the moisture content and the dry matter loss of biomass through the supply chain and are included in the model. The model is developed using an object oriented high level simulation language EXTEND™. A case of corn stover collection and transport scenario using baling system is described.

Keywords: Biomass logistics; Biomass collection simulation; Biomass transportation simulation; Biomass collection cost; Biomass transportation cost; Biomass delivered cost

1. Introduction

Recent advances in computational tools have made it possible to build mathematical models for analysis and optimization of complex supply systems. These tools are applied successfully to manufacturing, transportation, and supply chain management of many goods and services. This paper describes the implementation of these tools for simulation of supply and transportation of agricultural biomass. The agricultural biomass supply logistic consists of multiple harvesting, storage, pre-processing, and transport operations. The entire network operates in space and time coordinates. Agricultural biomass supply logistics are characterized by a wide areal distribution of biomass; time and weather-sensitive crop maturity; variable moisture content; low bulk density of biomass material and a short time window for collection with competition from concurrent harvest operations. An optimized collection, storage and transport network can ensure timely supply of biomass with minimum cost.

Tatsiopoulos and Tolis [1] evaluated the supply of cotton gin waste to small decentralized combined heat and power plants in Greece. Hansen et al. [2] developed a simulation model of sugar cane harvest and mill delivery in South Africa. Nilsson [3] described in detail the development of a simulation model (SHAM—Straw Handling Model) for baling and transporting wheat straw to district heating plants in Sweden. The simulation demonstrated the utility of systems analysis in predicting the amount and cost of biomass supply in optimum resource allocation to minimize bottlenecks. Nilsson's published model did not include bulk handling of biomass [4,5]. Mantovani and Gibson [6] modelled a collection system for corn stover, hay, and wood residues for ethanol production using the GASP IV simulation program. They considered historical weather data and farmers' changing attitude towards harvesting biomass. They highlighted the impact of weather variations and late harvest on biomass availability and equipment cost. Arinze et al. [7] and Sokhansanj et al.

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Nomenclature

A	area of the field processed (ha)
DML_{b}	maximum bale dry matter loss (decimal fraction mass basis)
DML_{f}	maximum harvest dry matter loss (decimal fraction mass basis)
DML_{s}	maximum storage (silage) dry matter loss (decimal fraction mass basis)
DML_{t}	time dependent dry matter loss (decimal fraction mass basis)
DML_{max}	maximum dry matter loss (decimal fraction mass basis)
E_{f}	efficiency of field equipment (decimal fraction)
E_{p}	evaporation rate (mm day^{-1})
E_{t}	efficiency of transport equipment (decimal fraction)
E_{w}	efficiency of service equipment (decimal fraction)
F	fraction of the land harvested (decimal fraction)
F_{c}	fuel and lubricating cost (\$ h^{-1})
H	hour of machine usage (h)
i	annual interest rate (decimal fraction)
K	fill factor (decimal fraction)
k	fraction of capital for annual taxes, warehouse for equipment (decimal fraction)
L_{c}	hourly labour cost (\$ h^{-1})
M_{e}	equilibrium moisture content (decimal fraction dry mass)
M_{i}	internal moisture content (decimal fraction dry mass)
M_{in}	initial moisture content (decimal fraction dry mass)
M_{s}	moisture content of stalks (decimal fraction dry mass)
M_{x}	external moisture content (decimal fraction dry mass)
M_{w}	moisture content of biomass (decimal fraction wet mass)
n	expected life of equipment of building (year)
Pe	precipitation (mm day^{-1})
P	purchase price of the equipment (\$)
P_{s}	saturated pressure of air vapour mixture (Pa)
P_{v}	vapour pressure of air vapour mixture (Pa)
q	mass of product processed (Mg h^{-1})
rh	relative humidity (decimal fraction)
R	annualized capital cost (\$ year^{-1})
S	salvage value (\$)
s	forward speed of equipment (km h^{-1})
t	time (min, hour, day)
T	temperature (°C)
t_{m}	preparation time (min)
t_{tr}	transport time (min, hour, day)
t_{haul}	haul time (min, hour, day)
t_{return}	return time (min, hour, day)
t_{ld}	load time (min, hour, day)
t_{uld}	unload time (min, hour, day)
u	air velocity (km day^{-1})
V	volume of container (m^{3})
V_{c}	variable cost (\$ year^{-1})
w	effective working width of equipment (m)
W_{b}	bulk mass of moist biomass (Mg)
W_{t}	bulk mass in transport (wet Mg h^{-1})
W_{b}	bulk mass (wet Mg)
x	day number (integer)
Y	yield (Mg ha^{-1})

Greek

ρ_{b}	bulk density of moist biomass (wet kg m^{-3})
ρ_{d}	bulk density of dry biomass (kg m^{-3})
ρ_{w}	density of water (kg m^{-3})

[8] modelled the changes in quality of potash fertilizer and alfalfa cubes, respectively, during storage and transport. The models considered weather data on timeliness of transport operations for these products but did not consider the entire supply chain.

Biomass Technology Group (BTG) [9] recommended a system analysis approach for reducing the costs, energy flow, and emissions of biomass operations. Berruto and Maier [10] and Berruto et al. [11] used a discrete simulation model to investigate how queue management could help to improve the performance of a country elevator receiving multiple grain streams with a single unloading pit. Humphrey and Chu [12] analysed the procurement and processing of corn in a wet milling operation using the simulation language GASP IV. Benock et al. [13] developed a GASP IV-based simulation model to analyse harvesting, on-farm transportation, and drying of corn. The model predictions agreed well with observations. Nilsson [4] and Hansen et al. [2] used the modelling language SIMAN. Rotz et al. [14] developed the dairy forage system model (DAFOSYM) based on the FORTRAN and BASIC languages.

The overall goal of this paper is to simulate the flow of biomass from field to a biorefinery. The specific objectives of this paper are:

- Develop a framework for a dynamic Integrated Biomass Supply, Analysis and Logistics model (IBSAL).
- Model climatic and operational constraints that have significant influence on the availability of biomass to a biorefinery.
- Develop a model to quantify resource allocations (such as labour, equipment and structure) for biomass supply and transport operations, and calculate biomass

delivered cost ($ Mg^{-1}). Note that biomass delivered cost in this study do not include any payment to the farmer or farming cost.
- Show the operation of the model with a case study of corn stover supply to a biorefinery.

2. The supply model

2.1. Overview

The IBSAL model is a simulation of a biomass supply chain. It consists of a network of operational modules and connectors threading the modules into a complete supply chain. Each module represents a process or an event. For example, grain combining, swathing, baling, loading a truck, truck travel, stacking, grinding, sizing, storing, each process is a module. Modules may also be processes such as drying, wetting, and chemical reactions such as breakdown of carbohydrates. Costing and energy calculations common to all operations are gathered into individual modules as well. Each module is independently constructed as a black box with a set of inputs and outputs. The module may also interact with an external spreadsheet to receive data or print data to the sheet. The biomass flows from one module to the next through a connector.

The model starts by defining the logistical features of the biomass supply such as number of farms involved, average yield, start and progress of harvest schedule, and moisture content of the biomass. The model also requires daily weather data that includes air temperature, relative humidity, wind speed, rainfall, and snow fall. This information is used in calculating drying and wetting of the biomass and trafficability of the soil. The user also defines the safe moisture content for baling and minimum temperature below which working on the field becomes impossible. A spreadsheet containing equipment specifications provides data for calculating service time for each operation. Once all the input parameters are identified, the model calculates the costs ($ Mg^{-1}), energy input ($MJ\,Mg^{-1}$), and emissions ($kg\,C\,Mg^{-1}$). All mass and moisture contents presented in this paper are, respectively, in dry Mg and decimal fraction (dry mass), unless otherwise specified.

The model is developed using an object oriented high-level simulation language EXTEND™ [15]. The biomass collection and supply system is divided in two activities: (1) collection and storage of biomass and (2) preparing and transporting of biomass from field to a biorefinery. The collection processes start immediately following the grain harvest or wilting of grass in the field. The model execution is fast, highly interactive, and allows changes in input and output as the program executes.

Fig. 1 is a block diagram of the main components of the IBSAL modules. The main components of the inputs are described on the left and outputs from the modules are listed on the right. The central IBSAL block represents the

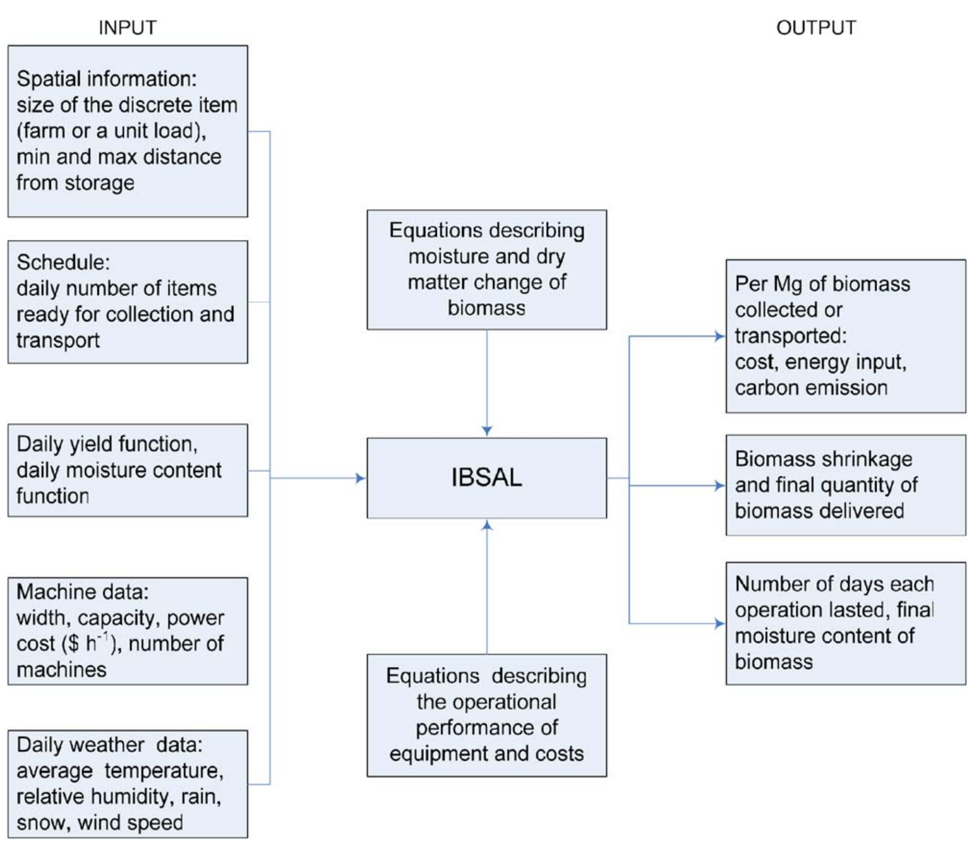

Fig. 1. Overall structure of IBSAL collection modules defining input and output.

assembly of operations that simulates the movement of the biomass from field to biorefinery. The default values for input data are already available in a module. The equations describing biomass modifications and the operations are built in the program. The above information can be modified if a user wishes to include new input data or new equations. The operational characteristics of the IBSAL central block for transport model are the same as those in the collection model. The input data are slightly different from the data for collection. The output format is identical to the collection module.

In the following sections we describe the development of the elements of the IBSAL model. We use collection and transport of corn stover to illustrate the concepts used in the model development.

2.2. Biomass availability

The start of the grain harvest depends upon local climate and kernel moisture content. Corn grain matures and becomes harvestable when the moisture content of kernels drops to 40%. Farmers prefer to complete harvest as quickly as possible to have time to prepare the land for the next crop. Harvesting operations may continue until cold, rainy, or snowy conditions make field operations difficult. The harvest season for corn may range from early July in Southern states to late November in the Midwest and Great Lakes regions of the USA.

The National Agricultural Statistics Service of the US Department of Agriculture publishes historical data on weekly progress of major crops during growing season [16]. The maturity dates and the weekly harvest progress for each crop can be found on the National and State Data pages. For the State of Iowa, the tabulated data indicated that in 2002 corn grain matured and was ready for harvest starting August 25. Fig. 2 shows the cumulative percent of farms harvested in Iowa. We needed the percentage of farms harvested daily. We fit a gamma distribution function to the weekly data to estimate the daily percent harvested. The gamma distribution is defined as follows:

$$F(x,a,b) = \int_0^\infty \frac{1}{b^a \Gamma(a)} x^{a-1} \mathrm{e}^{-x/b}\, \mathrm{d}x, \qquad (1)$$

where x is in days, a and b are parameters. $\Gamma(a)$ is the gamma function.

We used the GAMMADIST function and the toolkit SOLVER available in MS EXCEL to estimate the parameters a and b. The resulting coefficients were: $a = 7.5253$ and $b = 5.3542$. Fig. 2 shows the curve representing the gamma distribution using the estimated a and b parameters.

2.3. Moisture content of stover

For simulation, we considered the moisture content of stover in two stages: (1) moisture content of stover prior to grain harvest (standing stover) and (2) moisture content of stover after grain harvest (stover laid on the ground).

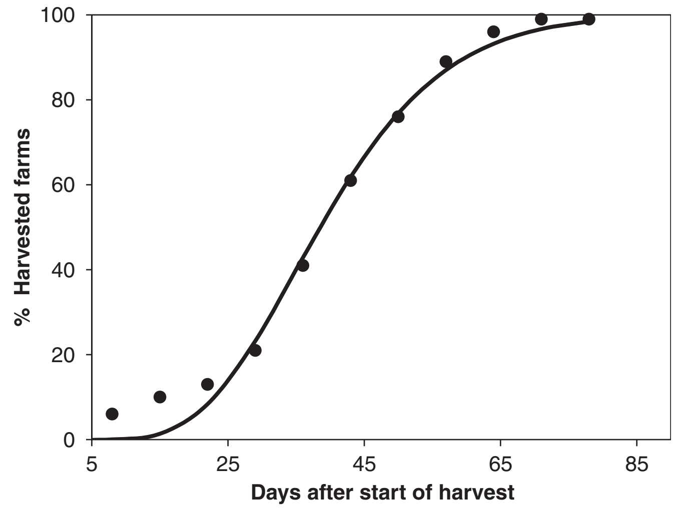

Fig. 2. Data on weekly cumulative percentage of farms harvested in Iowa and the gamma distribution function fitted to the data (Day 0 is September 15, 2002).

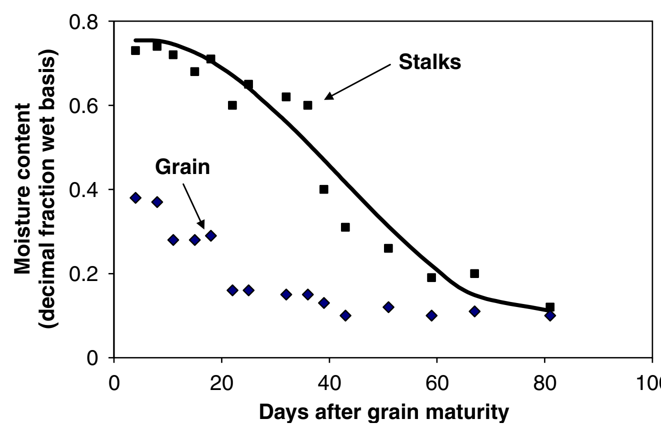

Fig. 3. Moisture content of corn stalks (solid line and filled boxes or squares) and of the grain (filled diamonds) after grain maturity date.

Moisture content of stover at the time of harvest: Pordesimo et al. [17] monitored the moisture content of grain and stover after grain reached its physiological maturity that is roughly 40%. They removed samples from the whole plant and fractionated it into grain, leaf, cob, husk, and stalk fractions. Mass and moisture content of these fractions were measured. Fig. 3 plots the data for the moisture content of kernels and stalks. The study also recorded weather conditions that included temperature, relative humidity, and rainfall. The moisture content decreased as the harvest season progressed. A third-degree polynomial represents the moisture content of the stalks as a function of day number after the start of harvest.

$$M_\mathrm{w} = (3.34 \times 10^{-6})x^3 - (4.3 \times 10^{-4})x^2 + (4.47 \times 10^{-3})x + 0.7432$$
$$R^2 = 0.98, \qquad (2)$$

where x is day number ($x = 0$ for the first day of grain harvest). M_w is the average moisture content of the stalks. The plot of Eq. (2) in Fig. 3 shows the fit of the curve to the moisture content data for stalks.

Moisture content of stover after grain harvest: For grain harvest, the combine harvest mechanism pinches the stalks from just below the lowest ear along the stalk. A large portion of the stalk remains standing and the rest of the biomass is cut and spread out in pieces. In many cases, the standing portion of the stover is firmly anchored to the ground. Shredding stover using a flail chopper prior to baling is a common practice in Iowa where limited quantities of stover are harvested for animal bedding or feeding. The in-field drying rate of stalks after combining has not been studied extensively [18]. Sporadic data or anecdotal information indicates that broken stalks lose moisture easier than the standing crop. Shinners et al. [19] have shown that the shredded stalks become wet faster than the standing crop after rain.

Nilsson [3] reviewed literature on drying and wetting of biomass (wheat straw) and concluded that instantaneous moisture content of straw can be divided into external and internal moisture content. For initial conditions, 80% and 20% of the initial average moisture content was assigned to the stalk's internal and surface moisture content, respectively.

$$M_i = 0.8M_{in}; M_x = 0.20M_{in}, \tag{3}$$

where M_{in} is the average initial moisture content of kernel at $t = 0$. For internal moisture content, Nilsson [3] used the following well-known first order drying equation.

$$\frac{dM_i}{dt} = -aE_p(M_i - M_e), \tag{4}$$

where a is a constant and E_p (mm d^{-1}) is pan evaporation, M_e is the equilibrium moisture content, M_i is the internal moisture content. To estimate the parameter a, Nilsson used the in-field drying data for straw during daytime with no recorded precipitation. The results yielded $a = 1.2\,\text{mm}^{-1}$. For the surface moisture, Nilsson developed a mass balance by equating the rate of moisture change on the surface of straw to inflow and outflow rate of moisture.

$$\frac{dM_x}{dt} = bPe - cE_p, \tag{5}$$

where Pe is precipitation rate (mm d^{-1}) and E_p is evaporation rate (mm d^{-1}). The constants b and c were measured during and after precipitation, $b = 23\,\text{mm}^{-1}$ and $c = 18\,\text{mm}^{-1}$. Nilsson used Henderson–Thompson's equation [20,21] to calculate the equilibrium moisture content M_e for use in Eq. (6),

$$M_e = \frac{1}{100}\left[\frac{\ln(1 - rh)}{-k_1(T + k_2)}\right]^{k_3}, \tag{6}$$

where rh is relative humidity (decimal fraction) and T is ambient air temperature (°C). Nilsson used published values for field drying of wheat straw as $k_1 = 2.8 \times 10^{-4}$, $k_2 = 2.8 \times 10^2$, $k_3 = 1.03$. The applicability of these values to corn stover has not been tested.

Pan evaporation: For E_p, the rate of water evaporation from a free surface, we used the following empirical equation suggested by Holman [20]:

$$E_p = (3.21 + 0.078u)(P_s - P_v)^{0.88}, \tag{7}$$

where E_p is evaporation rate (mm d^{-1}). The independent variables are the mean wind velocity u (km day^{-1}), P_s and P_v are saturated water vapour pressures (kPa) at dry bulb and wet bulb temperatures, respectively. Psychometric relations in ASAE [22] were used to calculate P_s and P_v from dry bulb, wet bulb and relative humidity data.

2.4. Weather factors affecting field operations

Hourly weather data was extracted from TMY2 (Typical meteorological year) [23], and integrated to generate daily average dry bulb temperature (°C), daily snowfall (mm), daily average relative humidity (decimal fraction), daily evaporation (mm), and daily rainfall (mm). In the model, we assumed one working hour delay due to 1 mm of rainfall. For example, a 10 mm rainfall delayed a field operation by 10 h. We also assumed 1 mm of snowfall delayed a field operation by 2 h. A day was considered to be a non-working day when the average dry bulb temperature for that day drops to less than −10 °C. The operations resumed when warmer conditions prevailed. Mantovani and Gibson [6] reduced the number of working days in a harvest season by the number of rainy days. Nilsson [3] implemented a much more elaborate strategy to schedule field operations during rainy periods.

2.5. Equipment performance

In a discrete modelling sense, we are interested in the time that an operation takes to cover a certain area of the field or process a certain tonnage of material. For equipment that work in the field the performance is calculated from the width of cut and ground speed of the equipment [22]:

$$t = C_1\frac{A}{swE_f} + t_m, \tag{8}$$

where A is the covered area (ha), s is the equipment speed (km h^{-1}), w is working width (m), and E_f is field equipment efficiency (decimal fraction); t is the time the operation has been done, C_1 is a coefficient to convert to minute, hour, or day, t_m is the time in the field for operations other than travel time. For example, the time a round baler requires to tie or to wrap a bale.

ASAE [22] publishes an estimate of performance data for agricultural equipment. Table 1 is extracted from the published data in ASAE for equipment whose performance depends on the speed. Speeds that affect the field performance of travelling equipment vary widely. Table 1 also lists typical efficiencies. Efficiencies are measured in

Table 1
Speed, efficiencies, throughput, and hourly cost of equipment used to simulate collection and transport of stover in this paper

Equipment	Power (kW)	Efficiency (%)	Throughput capacity ($Mg\,h^{-1}$)	Typical speed ($km\,h^{-1}$)	Bulk density ($kg\,m^{-3}$)	Hourly cost rate ($\$\,h^{-1}$)
Baler-square	137	75	14	7	128	83.66
Grinder (self powered)	213	85	20	—	0	106.13
Loader-bale	91	85	2	—	0	44.92
Flat bed truck	266	85	36	60	128	48.40
Stacker	266	85		8	0	121.96
Shredder	61	80	40	11	0	35.84
Grain combine	266	65		5	672	127.35

terms of time during which useful work is done over the total time spent in the field.

Crop yield (crop density) affects the speed of field equipment. Operators vary field speed in order to make the equipment to run at or close to the design capacity. For example, baler field speed can be estimated from:

$$s = C_2 \frac{q}{wY}, \tag{9}$$

where q is the amount biomass processed per hour ($Mg\,h^{-1}$), Y is the biomass yield ($Mg\,ha^{-1}$), w is the width of cut (or effective width of shredder). C_2 is a coefficient for unit consistency. In Eq. (9), w is also a function of Y. In other words, the width of cut is chosen such that adequate material is in the swath so a baler can operate at a reasonable speed and perform at its rated capacity. Jenkins [24] suggests a linear relation between the width of cut (w) and the biomass yield (Y) at a given speed:

$$w = -m_1 Y + m_o, \tag{10}$$

where m_1 is the slope and m_o is intercept of the line. Jenkins [24] mentions that Eq. (10) holds only for low and moderate yields.

Equipment service time is calculated by

$$t = \frac{AY}{qE_w}, \tag{11}$$

where A is the area covered (ha), Y is the net yield ($Mg\,ha^{-1}$), q is the unit throughput ($Mg\,h^{-1}$), E_w is the efficiency of equipment (decimal fraction), and t is service time (h).

2.6. Transport equipment performance

Transport time consists of travel time, load time, and unload time.

$$t_{tr} = \frac{t_{haul} + t_{return} + t_{ld} + t_{uld}}{E_t}, \tag{12}$$

where t_{tr} is the total transport time per load (h), t_{haul} and t_{return} are the forward and return time of the transporter per load (h). t_{ld} and t_{uld} are loading and unloading times per load (h). E_t is an efficiency factor for a transport equipment, whose value is less than 1 considering turns and obstacles that increase transport time.

Transporter capacity, W_b, is expressed in terms of mass (as is) to be transported.

$$W_b = k\rho_b V. \tag{13}$$

W_b is the wet mass (Mg) of the biomass, ρ_b is the wet bulk density of the biomass ($Mg\,m^{-3}$), and V is volume of the container (m^3). Coefficient $k<1$ represents less than full situations and deviations from a straight plane for the top of the load in the transporter. In the absence of data on bulk density of biomass at a given moisture content, we assume that volume remains unchanged at different moisture contents. The wet bulk density can be estimated from:

$$\frac{1}{\rho_b} = \frac{1 - M_w}{\rho_d} + \frac{1}{\rho_w}, \tag{14}$$

where ρ_b is the bulk density of biomass at moisture content of M_w (decimal fraction mass basis), ρ_d is the dry bulk density ($kg\,m^{-3}$) of biomass, and ρ_w is the bulk density of water ($1000\,kg\,m^{-3}$). The effective transport rate is the ratio of transport capacity and the total transport time.

$$W_t = \frac{W_b}{t_{tr}}. \tag{15}$$

W_t is the rate of mass transport (wet $Mg\,h^{-1}$). It should be noted that W_b has a maximum value based on legal weight limits. In other words if W_b exceeds the legal limits then V or k has to be reduced.

2.7. Dry matter loss

Biomass loses dry matter as it undergoes various operations. Leaves and other fragile parts of the plant are broken and lost in the wind or mixed with soil during collection processes. Some of the losses occur during storage due to fermentation and breakdown of carbohydrates. Unfortunately, the exact account of stover losses in the field or during storage is not available. In one study [25] roughly 3/4 of the leaf fraction was lost when the standing corn stalk dried in the field over a period of 1 month. Dry matter loss data are available for alfalfa [26]. Fig. 4 is the digitized data in references [26,27] to which the following empirical equations was fitted.

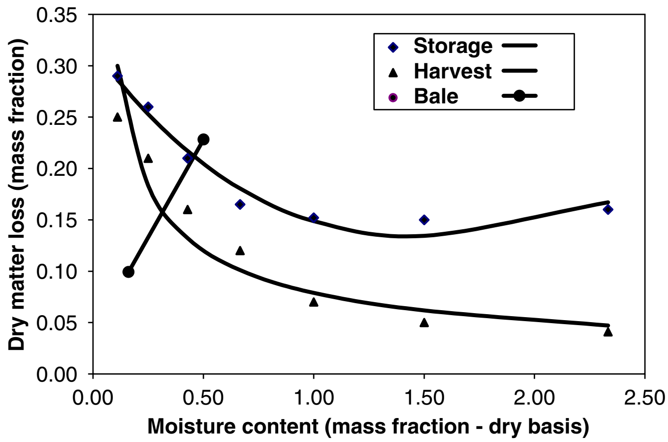

Fig. 4. Harvest and storage dry matter losses for forage and stover. (Data for harvest and silage losses are adapted from [26]; data for dry matter losses in bales are adapted from [27].)

For field or harvest losses:

$$DML_{\mathrm{f}} = 0.079 M_{\mathrm{s}}^{-0.06073}, \quad R^2 = 0.94. \tag{16}$$

For storage (silage) losses:

$$DML_{\mathrm{s}} = -0.0181 M_{\mathrm{s}}^3 + 01381 M_{\mathrm{s}}^2 - 0.2877 M_{\mathrm{s}} + 0.3164 \quad R^2 = 0.97 \tag{17}$$

and for stored bale losses:

$$DML_{\mathrm{b}} = 0.3793 M_{\mathrm{s}} + 0.0368 \quad R^2 = 1.00. \tag{18}$$

M_{s} is the moisture content of stalks (fraction dry mass). DML_{f}, DML_{s}, and DML_{b} stand for dry matter loss (mass fraction) in the filed, in storage, and for baled biomass, respectively. The time scale for the predicted dry matter loss using Eqs. (16)–(18) is not known. We assume the calculated values to be the maximum dry matter loss after 6 months. We also assume dry matter loss approaches a maximum value asymptotically as shown in equation below:

$$DML_{\mathrm{t}} = DML_{\mathrm{max}}(1 - \mathrm{e}^{-t/180}), \tag{19}$$

where DML_{t} is time-dependent dry matter loss. t is time after the start of the harvest or storage (days). DML_{max} is replaced by DML_{f} from Eq. (16), DML_{s} from Eq. (17), and DML_{b} from Eq. (18).

2.8. *Costing method*

The cost calculations follow the traditional method of dividing costs into two separate components: fixed costs and variable costs. The fixed cost is the total cost of ownership that is independent of the usage of equipment. ASAE [22] recommends an annual cost to be calculated as follows:

$$R = \left[P - \frac{S}{(1+i)^n}\right] \frac{i(1+i)^n}{(1+i)^n - 1} + Pk + \frac{Si}{(1+i)^n}, \tag{20}$$

where R is the annual fixed cost representing initial investment (\$ year^{-1}), P is the purchase price of equipment (\$), i is the annual interest rate (fraction), and k is the sum of rates for taxes (0.01), housing (0.0075), insurance (0.0025). The salvage value S is a fraction of the initial purchase price.

The variable costs are those associated with the use of equipment: repair and maintenance, fuel, lubrication, labour and the cost portion of tractors used to pull and power the equipment. ASAE [22] provides an elaborate method for estimating annual maintenance and repair cost. Hunt [28] provides the following simplified approximation for the variable costs for machinery.

$$V_{\mathrm{c}} = (0.0002P + 1.2L_{\mathrm{c}} + 1.15F_{\mathrm{c}})h, \tag{21}$$

where V_{c} is variable cost that depends upon the hours the machine is in service. The terms in the parenthesis are: $0.0002P$ for repair and maintenance; L_{c} is the hourly labour wage assuming 1.2 labour hours per machine hour; F_{c} is fuel and lubricating (15% of the fuel) cost; and, h is the hours of machine usage. For buildings, the annual usage cost is roughly 3% of the initial capital cost [22]. Table 1 lists the cost rates calculated for equipment used to collect and transport biomass. Details on the initial purchase cost, expected life of equipment can be found in references [29,30].

3. Implementation

Fig. 5 shows the flow of biomass through the collection network. The discrete item in our simulation is 10 ha. Attributes of the discrete item (land) are moisture content, yield, minimum and maximum distance from a stacking (or storage) location. As an item enters the network, the corresponding weather data is also read in. The item becomes an accumulator of costs as the item passes through each station (also known as activity-based costing [31]). For example, an item that is worked on by balers, the cost of balers is added to the cost that the item has so far accumulated from previous operations.

3.1. *Collection*

We assume 1000 productions units each 10 ha in size. The yield of stover is 5.7 Mg ha^{-1} [32]. The collected biomass is stacked at the side of the farm. The bale collector/transporter/stacker scavenges the field with $x = 0.1$–1.6 km and $y = 0.1$–1.6 km. We assume a winding factor of 1.2 between the farm and stack yard. Table 2 is a summary of IBSAL's output for collection operations. Table 2 lists the completion dates for each operation. Size, speed, and number of equipment make it possible to complete each operation at a specific date. We specify 3 shredders, 8 balers, and 4 bale stackers to complete the collection operations by November 21. The initial tonnage is 56.777 Gg. The final stacked quantity is 54.555 Gg, a dry mass loss of about 4%. The overall cost of biomass collection is 21.12 \$ Mg^{-1}. Of the total combine costs 10% is allocated to the cost of stover harvest and the other 90%

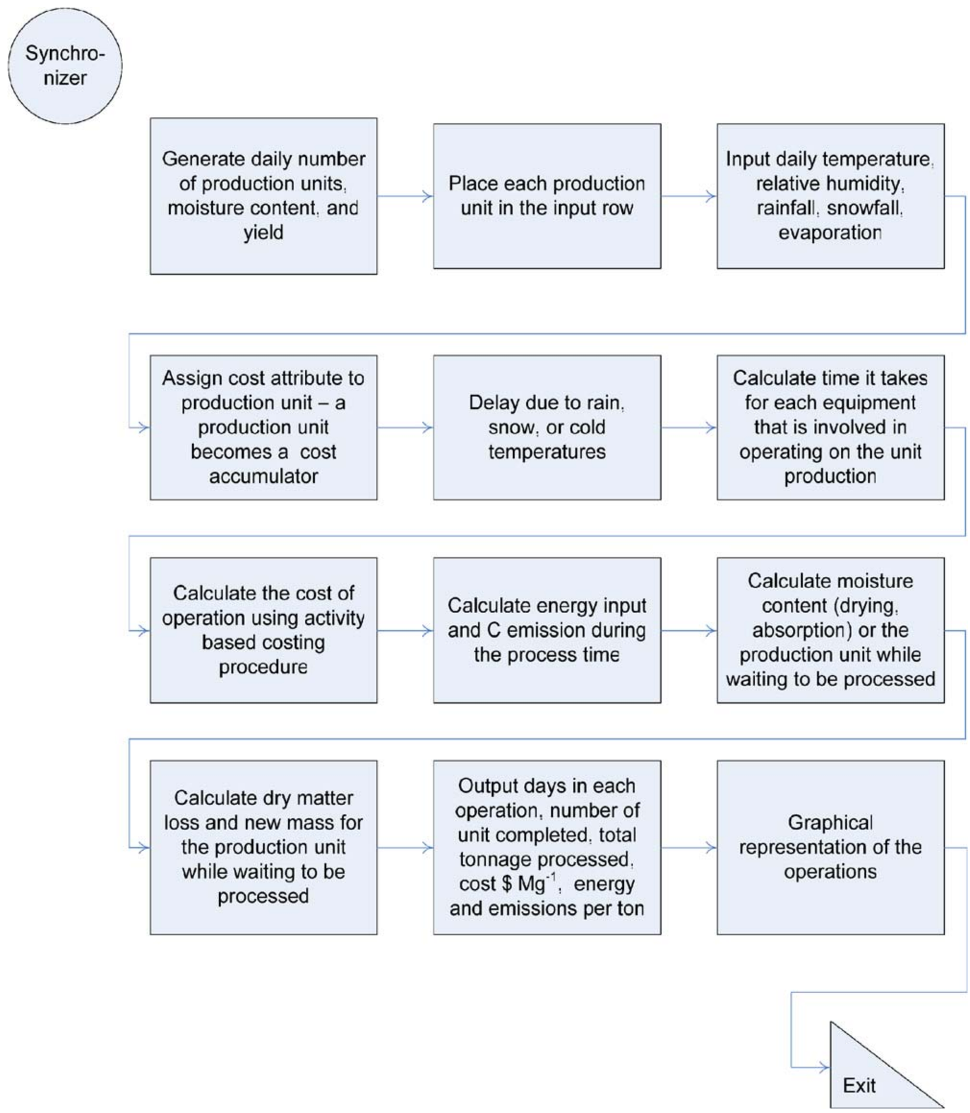

Fig. 5. Simulation of biomass flow through a collection program.

Table 2
Completion day, cost, energy input, emissions and dry matter for a conventional baling system for corn stover at a yield of 5.7 $Mg\,ha^{-1}$

Operation[a]	Date completed	Mass (Mg)	Cost ($\$\,Mg^{-1}$)	Energy input ($MJ\,Mg^{-1}$)	Carbon emission ($kg\,C\,Mg^{-1}$)
Combine[b]	November 5	56,777	1.47	48.0	1.035
Shredding	November 9	55,262	1.23	17.6	0.375
Baling[c]	November 18	54,573	9.01	124.9	2.645
Stacking	November 21	54,555	9.16	169.1	3.590
Overall			21.12	364.4	7.275

[a]No. of equipment: combines 22; grain trucks 8; shredders 3; balers 8; stackers 4.
[b]Start of harvest is September 15.
[c]Square bale.

to the grain harvest. Cost of cutting and shredding biomass in the combine is also 10% [31].

Table 2 lists the amount of energy input to the power equipment. We note that the energy input for corn stover is 364.4 $MJ\,Mg^{-1}$. To put this energy use in perspective, the amount of energy in a dry Mg of dry stover is roughly 17 GJ. The amount of energy used to power equipment is roughly 2% of the energy content of biomass. Table 2 also lists the amount of carbon emission as a result of using diesel fuel.

Table 3
Completion day, cost, energy input, emissions and dry matter for transporting and grinding of baled stover from stacks

Field operations[a]	Completion day[b]	Total biomass (Mg)	Cost ($ Mg^{-1})	Energy input ($MJ\,Mg^{-1}$)	Carbon emission ($kg\,C\,Mg^{-1}$)
Load	124	450,900	3.59	154.5	12.050
Truck travel	342	430,989	13.76	640.6	49.875
Unload	342	430,989	3.58	199.6	15.585
Stack	342	430,989	0.44	7.5	0.585
Grind	343	430,989	10.92	185.7	14.450
Overall			32.45	1087.5	93.135

[a]No. of equipment: bale loaders at the farm site 2; flat bed trucks 13, unload and stackers 5, grinders 3.
[b]Number of days after start of transport.

3.2. Transport

The biomass that has been collected during the harvest season and stored next to the field or at satellite storage sites is loaded onto trucks and transported to a biorefinery. For bale transport, bales are stacked on a flatbed trailer to the maximum height of 4 m (above ground). Roughly 36 rectangular bales ($1.2 \times 1.2 \times 2.4$ m) are placed on a 14.6 m long flat bed. Larger trailers with more axles are available when allowed by local transport regulations. Front-end loaders equipped with special bale grabbers remove bales from the stack and place them on the deck of the trailer. The stacks are tied down with straps. The bales are transported to the biorefinery on public roads.

Once at the biorefinery, the truck may be weighed before unloading; the bales are unloaded and stacked. Unloading and stacking at the biorefinery may be done using a large crane with bale grabbers, with the whole truck being unloaded at once. For the present analysis, we assume that a front-end loader is used to unload bales and stack them at the biorefinery. In preparation for processing, the bales are removed individually from the stack and loaded onto a stationary grinder/shredder. The ground biomass is sent to the first stage of biorefinery.

Table 3 shows the output of IBSAL simulating transport and grinding of the baled stover. In this particular example, 450.9 Gg of biomass was transported from roughly 500 storage sites (800 Mg in each site) to a biorefinery. The distance travelled ranged from a minimum of 32 km to a maximum of 160 km. We assumed the storage sites are randomly distributed with a multiplier of 1.4 for winding roads. The number of equipment listed at the bottom of Table 3 was selected to deliver biomass to biorefinery in equal amounts daily throughout the year.

The cost of transport is 32.45 \$ Mg^{-1} of which 10.92 \$ Mg^{-1} is for grinding. For transport alone, it is roughly 4.00 \$ Mg^{-1} each to load and unload and travel alone is 13.76 \$ Mg^{-1}. The total energy input is 1.0875 $GJ\,Mg^{-1}$ that is roughly 6.5% of the energy content of the dry biomass. Most energy input and carbon emissions are spent on transportation. The total biomass loss calculated in our example is less than 4%.

4. Conclusions

The objective of the present work was to develop a dynamic simulation program for collection and transportation of large quantities of biomass and to predict the delivered costs (\$ Mg^{-1}). We compiled weather and yield data from published sources. We also developed equations representing the working rate of field machinery and transport equipment. We calculated fixed and variable costs to represent labour, equipment, and structures. A commercially available simulation package EXTEND™ was used to implement the supply model. We modelled a case of harvesting corn stover using a shredder, large square baler, and automatic stacker. The biomass was gradually trucked from stacked areas to a biorefinery for 360 days. The following conclusions can be drawn from this work.

- EXTEND™ software provides a convenient object-oriented language to implement the dynamic simulation of biomass supply.
- The model considers time-dependent availability of biomass and the effects weather conditions have on the progress of harvest.
- The program predicts the number and size of equipment to meet the rate of harvest and biorefinery demand schedule for feedstock.
- The delivered cost of biomass is calculated based on the utilization rate of the machines and storage spaces.

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