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ScienceDirect
Biomass and Bioenergy 30 (2006) 838–847
BIOMASS & BIOENERGY
www.elsevier.com/locate/biombioe

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

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Received 26 March 2005; received in revised form 17 April 2006; accepted 25 April 2006
Available online 15 August 2006

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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doi:10.1016/j.biombioe.2006.04.004

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