A web-based tool for biomass production systems

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A WEB-BASED TOOL FOR BIOMASS PRODUCTION SYSTEMS

Berruto R[1]; Busato P[1]

[1]University of Turin, School of Agriculture, DEIFA Department, Via Leonardo da Vinci 44, 10095, Grugliasco, Turin, Italy

Abstract

In this paper, a web-based tool is presented for the estimation of biomass production and transportation costs with regard to input requirements, internal processes, and output. The tool relates to the production, harvest and out-of-field transport of biomass in multiple-crop production systems and focuses on details of the individual production units such as distance from associated facilities, soil conditions, machinery system, and labour types. By testing various alternatives, the tool can support decisions for biomass production systems on a strategic level (e.g., number and dimensioning of machines, machine capacity, crop selection, and labour requirements), tactical level (e.g., fertiliser/chemical application plans and labour budgets), and operational level (operations specifications). This work was part of the collaborative Intelligent Energy Europe Programme project BioEnergy Farm.

Keywords: bio-energy; farm management; biomass supply chain; field logistics

1. INTRODUCTION

Biomass production for the generation of bio-energy must adhere to economies of scale requiring a large, arable area dedicated to the supply of “raw material”. This characteristic increases the geographic dispersion of the fields dedicated to biomass production, which increases the need for long-distance transportation. Due to the wide spatial distribution of the fields that constitute biomass production areas, the transportation of biomass has to be carried out through a non-uniform network. In addition, a specific order of different crops is required within the biomass production system to more effectively secure the availability of raw material throughout the year and to provide the raw material for different types of bio-energy production processes.

Research has shown that the engagement of farmers in biomass supply chain activities, specifically in the collection and transportation of products [1,2], provides cost-effective solutions for supply chain activities that increase the farmers’ income and reduce the ownership cost of machinery because of increased usage. However, agriculture has not traditionally used formalised planning tools for logistics management, and the decision-making process associated with the planning remains very much implicit and internalised [3-5]. Therefore, easy-to-use tools for different planning levels should be available for farmers and farm managers.

A number of models and modelling approaches dedicated to decision-making processes within the biomass supply chain system have been introduced. In [6] a biomass logistics model to simulate the collection, storage, and transport operations for supplying agricultural biomass, was developed which included stochastic aspects such as the influence of weather conditions, the moisture content, and the dry-matter loss of biomass through the supply chain. Taking into account the same stochastic factors, in [7] the changes in quality of potash fertiliser and alfalfa cubes during storage and transport have been modelled. In order to investigate the effect of queue management on the system’s performance, in [8] a discrete simulation model for a country elevator receiving multiple grain streams with a single unloading pit was developed. In [9] a decision-support system was developed by implementing a modelling suite for determining the optimal time for initiating various operations related to the harvesting and treatment of biomass based on biomass moisture content predictions that incorporated the uncertainty of weather conditions. A number of models have been developed for specific crop types. A GIS-based cost-estimation model for the collection and transportation of switch-grass has been developed and described in [10]. A discrete event-simulation model of the harvesting and transportation systems of sugarcane that focused on the amortisation and efficiency of the machinery has been developed in [11]. In [12] a Monte Carlo simulation to estimate the probability distribution of corn-stover feedstock costs was developed using alternative assumptions for key parameters involved in harvesting and transportation.

All of the previously mentioned approaches tackle different aspects of the system's complexity (e.g., weather dependency, stochastic demands, etc.) and different functional areas of the biomass supply chain (i.e., production, harvest, storage, and distribution as defined in [13]) that reference single- or multiple-crop systems. Furthermore, different tools provide decision support at different planning levels, such as at the strategic, tactical, and operational levels [14]. The work presented here relates to the production, harvest and out-of-field transport of biomass in multiple-crop production systems and focuses on detailed characteristics of the individual production units. A web-based tool is presented for the estimation of biomass production and transportation costs with regard to input requirements, internal processes, and output.

2. SYSTEM DESCRIPTION

2.1 OVERVIEW

The overall structure of the web-based decision-support system is illustrated in Fig. 1. The input information is provided by the user in a series of web pages that include appropriate forms (Fig. 2 shows a selected input-data web-page). The input parameters are distinguished according to four types: i) descriptive, ii) numerical, iii) selective, and iv) binary. The selective parameters are chosen by the user from provided lists. These parameters are used by the tool for the subsequent selection of various coefficients from databases included in the tool. For the user's convenience, a number of the provided lists have been built by the tool during the input process based on information previously provided by the user. For example, when an operation is allocated to a crop (in the "field-operations" data set), the user can select the crop from the list created by the system because the list includes crops that have been inserted by the user (in the "crops" data set).

The underlying models of the system have been developed using the object-oriented language ASP.NET MVC using an SQL Server database. All the computation is performed on the server side by means of a set of functions and storing procedures.

2.2 INPUT

The initial data sets include the general information for the production system under study, the definition of the crops that will be produced and the individual fields included in the production system, and the allocation of crops to field areas (Fig. 3). To produce a user-friendly input, the tool allows users to insert input data in more than one form depending on either personal preferences or the type of available data. For example, in the case of fertiliser application, the dosage for the total area allocated to the crop to which the fertiliser is applied can be defined as either t/ha or as t. Based on data that have been previously provided by the user, the tool assigns the input to the appropriate unit of measurement.

2.2.1 Land and crop data

2.2.1.1 "User Profile" data set

The information provided in the application's "user profile" data set is limited to username, password, email and language interface. Based on the country selected, the system applies the appropriate databases listed by the country code, such as country-specific coefficients (e.g., range of crop yield per country), energetic coefficients, and currency (e.g., EUR, DKK, USD, PLN, etc.). The user can choose to remain anonymous or share information with other users based on a specific key number assigned to the profiles.

2.2.1.2 “Production system” data set

The information provided by the user in the “production system” data set includes the numerical parameters of interest rates and fuel prices and the selective parameters of the preferred currency. Users can to either allow open access of their registration to other users (shared ← YES) or not allow access (shared ← NO). The selection of the “frozen” binary parameter does not allow changes to parameters and only permits read-only access to prevent accidental changes. However, the user can de-select this feature and make any changes to the input parameters. If a production-system scenario has been selected as shared, it is automatically frozen for all users except the owner.

2.2.1.3 “Field” data set

The information for each individual field of the production system is provided in the “field” input data set. The numerical input parameters provided include the field-area dimensions, the headland width of the field, the distance from the machinery station or farm, and the average speed for the transfer of the machinery to and from the machinery station. The field’s soil texture is classified into one of three classes: fine, medium, or coarse [15]. Based on the soil texture classification, the tool selects from the corresponding database the adjustment parameter used to compute the power requirements and the fuel consumption of the machinery that operates in a specific field.

2.2.1.4 “Crops” data set

In the “crops” data set, the cultivated crops in the production system are iteratively selected by the user from a list provided by the web-tool database.

2.2.1.5 “Crops to fields” data set

In this input-generation step, the allocation of crops to each field is determined. In this data set, the user can combine crops that have been selected by the user in the “crop” data set with the fields of the production system that have also been generated by the user in the “field” data set. A given crop can be allocated to different fields, and conversely, a number of crops can be allocated to one specific field. Each production area of a field in which an individual crop is cultivated will be referred to as a “production unit”. For this reason, the area of a field that is allocated to a specific crop is defined by a numerical parameter. The other numerical parameters that are defined in this data set are the distance between the field and the destination of the crop (e.g., processing plant) and the year of rotation. The year of rotation applies to perennial crops (e.g., Miscanthus, meadows, and short-rotation forestry).

2.2.2 Resource data

In the next step, information relative to the resources used in the production system, including manpower, machinery, allocation of manpower to machinery, and productive means (Fig. 3), is provided by the user.

2.2.2.1 “Manpower” data set

In the “manpower” data set, the user assigns a cost to each type of labour used in the production system. The labour types include family, seasonal, and specialised and can be selected from a list provided by the tool.

2.2.2.2 “Tractors” data set

In this data set, the parameters of the available tractors for the production system are uploaded to the web tool. Each tractor is identified by the numerical parameters of purchasing cost, power, and time used for other activities not related to the production system under consideration. The latter information is used in the calculation of the fixed cost of the tractor and takes into account the actual annual use of the tractor. The vehicle type (2-wheel drive, 4-wheel drive, and crawler type) is also defined. The selections within this data set provide the correct coefficients required to compute the fixed and variable costs (e.g., the lifetime of the tractor, repair and maintenance coefficients, insurance cost, settled cost, etc.).

2.2.2.3 "Machinery" data set

In the "machinery" data set, the web tool provides the user with a selection of machines used in the production system. Similar to the tractor data set, the machinery types listed in this data set are connected with a database that provides all the correct coefficients for the calculation of fixed and variable costs and the data related to operational performance (e.g., turning time, loading time, set up times, etc.). Self-propelled machines, including combine harvesters, forage harvesters, self-propelled sprayers and organic liquid fertilisers, committed in the production system (if any) are also defined. A machine is identified by the value of purchasing cost, working width, hourly use for other activities, hopper capacity and type (in the case of input and output material flow operations), and power (in the case of the self-propelled machines). Up to four hopper types can be defined for an individual machine: fertiliser, herbicide, insecticide, and seed or grain for planting or harvesting, respectively. Finally, a labour type is allocated to each machine from the list created in the "labour" data set. In the machinery data set, the tank capacity of equipment devoted to logistics operations is not considered as an input parameter since it depends on the type of transported crop.

2.2.2.4 "Productive means" data set

Each productive mean is identified by the value of the cost. The tool database provides a list of potential productive means. However, the user can add a productive mean if it hasn't been included in the database. In addition, for each of the pre-existing productive means, the tool provides a number of available product names.

2.2.3 Operational data

Operational data refers to information related to field operations and logistics operations and includes the allocation of machinery to these operations and the assignment of these operations to different production units (Fig. 4).

2.2.3.1 "Field operations" data set

For each productive unit, a number of operations are defined. Each operation is characterised by a set of attributes that describes the operation's allocated "entities", which include the tractor or self-propelled machine applied in the operation, the implement (machine) to carry out the specific operation, the crop types to which this operation is applied, and the associated production units. These "entities" are provided by the tool in the lists created during previous stages of data insertion. In order to expedite the insertion of the data, when an operation is assigned to a crop, the tool assigns this operation to each production unit of the specific crop by default.

The numerical input parameters for each field operation are the operating speed, the working width, the number of repetitions (passes), the skipped area (the distance between what is skipped between two sequential field-work track traversals of the machine where a zero value corresponds to complete area coverage), the number of the labours committed to the operation, and the labour coefficient (the ratio between the total working time of the labour and the working time of the machine). The working width entered in the field operations data set is not necessarily the same as the working width in the machinery data set. The former provides the effective working width. The system, however, provides by default the number of the theoretical working width (pre-selected) that has been stored during the "machinery" data set completion.

2.2.3.2 "Logistics operations" data set

The logistics operations data set consists of three operational tasks: loading/unloading at the field (e.g., loading bales on a trailer and unloading organic fertiliser to the in-field application unit); loading/unloading at a destination point (farm or biomass plant); and transport. A logistics operation is characterised by a set of attributes that includes the type of tractor applied to a specific logistics operation, the machine (transport wagon, loader, etc.) that transports the crop, and the associated production units. The general numerical input parameters are the transport speed, the total quantity to be transported, the load per trip, the loading/unloading time in the field, the loading/unloading time at the destination (farm or plant), the number of the labour types committed to the transport tasks, and the labour coefficient. When the machine does not carry out one or two of the tasks (e.g., the transport task in the case of a loader), the tool does not request any parameter related to these tasks (e.g., the transport speed, load per trip, etc.). The product description refers to the section of crop such as the straw or grain that is transported.

2.2.4 External services and income data

In this step, any relevant information concerning any external service cost (e.g., drying) and product sale is provided to the tool (Fig. 5).

2.2.4.1 "External services" data set

In this data set, the tool provides a list of external services that are allocated to crops. For each service type, a cost is assigned as either a unit cost (€/ha) or a total cost for the crop (€). By default, all the production units of the selected crop are assigned to the service. However, the user can de-select certain production units that are not assigned to the service.

2.2.4.2 "Product sales" data set

Income can be derived from either direct product sales or subsidies. For each type of crop, a number of by-products, such as grain, straw, and crop residues, could be exploited. For each of the main products and by-products, the value of the sale price and the subsidy (if any) per unit are uploaded to the system. When the user defines a production sales data set for a crop, the tool uses this data for all production units of the specific crop by default. However, if more than one level of production exists for different production units of the same crop in the production system (e.g., rain-fed vs. irrigated fields), each level of production has to be entered as a different production sales data set.

2.3 STORED DATABASES

Embedded in the tool are a number of lists provided to support users when inserting the input data sets. These lists include external service-type expenses, manpower type, product type (e.g., hay, corn grain, corn stover, etc.), productive means (e.g., type of fertiliser, herbicide, fungicide, and insecticide), and tractor and machinery type (e.g., seed bed preparation machinery, ploughing machinery, fertilising machinery, etc.).

In order to avoid errors during the input data insertion, the tool includes a number of preventative measures. For example, all numerical inputs have predefined ranges. When the user defines the speed of an operation, the tool uploads from the embedded national database the correct range of operational speeds for the machine selected to carry out that operation. Another preventative measure requires that the measurement units be selected based on category. If the user chooses fertiliser in the “production means” data set, the unit prices are assigned by fertiliser type (e.g., €/t or €/kg for nitrogen-based fertiliser or herbicide, respectively).

Finally there are a number of tables providing values of coefficients involved in the estimation of the working time, machinery and tractor costs (specifically for the estimation of the fuel consumption), and repair and maintenance costs. Details on these data sets are given in the following section.

2.4 PROCESSES

2.4.1 Working times calculations

Initially, a process for the standardisation of the units of measurement is established (PW1) (Fig. 7). Establishing this process is essential because various unit options are provided to the user for selection. The tool transforms all of the units into a standard internal unit-measurement system.

The first required step is the estimation of the working time of each operation (including field operations and logistics operations) in each production unit (PW9) (Fig. 7). The calculation of the working time in the case of field operations (PW8) includes two types of task times: the effective in-field operation time (PW5), and the non-effective time (PW6) that is the ancillary times for in-field operations that includes times for loading/unloading (in the case of the material handling operations), machinery adjustments, travel from the machinery depot to the production unit, and the non-productive time that is allocated for headland turnings and manoeuvring. The effective time is estimated by calculating the working travel distance (based on the number and length of field-work tracks), the operating speed and the skipped fieldwork track intervals (as provided by the user in the “operations” data set). The estimation of the non-productive time during turnings in a specific field for a specific operation is based on the calculation of the number of turnings, which is a function of the machine’s working width and the field geometry, and corresponds to the specific machine turning time per turning from the embedded tool database. Other embedded tool databases used for the estimation of the field-operations working time include the time for in-field machinery adjustments and the time per loading/unloading tasks for the specific machine type.

In the case of the logistics operations (PW7), the operational time includes sub-task times for loading/unloading in the field, the loading/unloading time at the destination (i.e., farm, bioenergy plant, or storage facility), and transport times for both full tanker transport (from the production unit to the material transport destination) and empty tanker transport (from the material transport destination to the production unit). The transport time is a function of the transport distance and speed, the quantity of the product that has to be removed (as provided by the user in the logistics operations data set), and the capacity of the transport unit in terms of the specific product (as provided by the user in the machinery data set). The transport distance depends on the selection by the user of the transported material destination (or origin in the case of material input operations). In the case of logistics operations, there are three cases that depend on the machinery type: when the machine is used solely for the transport task, when the machine is used solely for the loading/unloading task, and when the machine is used in both transport and loading/unloading tasks. For the case of cooperating machinery (primary units and transport units) in material-handling operations (seeding, harvesting, organic fertilising, etc.), both field and logistics operations are performed. In the case of the logistics operations, there are no default data in the database because of the large number of different products that can be carried (e.g., round bales, large rectangular bales, corn silos, wheat grain, organic fertiliser, etc.).

2.4.2 Labour cost

The labour cost for an operation in a production unit is estimated based on the working time of the operation, the assignment of the labour type for the machine carrying out the specific operation, the associated hourly cost, and the labour co-efficient.

2.4.3 Machinery cost

A specific feature of the developed tool is the estimation of the actual annual cost of the machinery, which also includes the hours that the machine is used inside and outside of the production system under study. This means that each time an operation is added, the total annual use of the machine is re-calculated, and consequently, the machine's fixed and variable hourly costs are re-calculated. In order to perform the calculation, the total working time that a given machine is committed to all production units has to be estimated (PM1). Based on the total working time, the annual use of the machine (PM2) and the lifetime of the machine (PM3) is estimated, which allows the tool database to assess the total lifetime in hours of the given machine type.

In the next step, the fixed and variable machine costs are estimated. The fixed cost (interest and depreciation cost) is estimated based on the amortisation method given in [15] as a function of the machine lifetime, the annual interest rate, the ownership cost factor for taxes, housing, and insurance, and the salvage value of the machine at the end of its lifetime. The variable costs of the machine refer to the repair and maintenance costs because the other two aspects of the variable cost, the labour and fuel costs, are estimated separately. For the calculation of the accumulated repair and maintenance costs for the machinery used in field and logistics operations, the equation given by Agricultural Machinery Management Data ASAE Standard D496.3 ([16]) has been applied. For ease of use, the tool provides a database of repair and maintenance factors [15].

The same steps are also followed for estimating the total variable and fixed costs of the tractors (PM1, PM7, and PM8). For self-propelled machines, only the machine cost is estimated.

For the estimation of the fuel consumption, the equation for measuring specific volumetric fuel consumptions given by the Agricultural Machinery Management Data ASAE Standard (ASAE D497.6, 2009) was used. The following data are provided by the tool:

- The tractive efficiency (built upon ASAE D497, Clause 3, [15]) required for the operation that is needed for the estimation of the equivalent power-take-off (PTO).
- The rotary power requirement parameters for the estimation of the required power take-off (PTO) for the implement (built upon ASAE D497, Table 2, [15]).
- The soil texture adjustment parameter (built upon ASABE D497, Table 1, [15]) for the estimation of the implement draft for the specific soil category selected by the user in the field data set.
- The machine parameters (built upon ASABE D497, Table 1, [15]) for the estimation of the implement draft selected by the user machinery in the machine data set.

2.4.4 Economic balance

Finally, all costs associated with a production unit (machinery cost, productive means cost, and external services cost) are gathered, and for perennial crops, this cost is actualised. The income is also actualised, and the margin for each production unit is estimated.

2.5 OUTPUT

Table 1 lists the output parameters of the tool. In the output of the tool for an individual crop, partial expenses of the production system, which include the operations cost (the summation of all operations carried out for all production units of the specific crop), the service and productive means costs (the summation of all service and productive costs incurred in all production units of the specific crop), and the manpower cost (the summation of all manpower costs associated with production units of the specific crop), are provided. The margin resulting from the subtraction of the cost of total expenses from the total product sales and subsidies is also provided. The system is also able to provide the same output for each individual production unit of a crop, which is very useful for making comparisons of different production strategies for the same crop.

3. CASE STUDY

To demonstrate the tool's utility and capability, a case study of a real production system is demonstrated. The case study refers to a production system of 120 ha that uses 80 ha area for running a 200 kW biogas plant. The production system includes fields scattered at different distances from the farm (Fig. 8; Table 2).

The yearly rotation is considered equal for all of the fields because only annual crops are included in the present study. The fields are cultivated with corn silo in summer and are partly cultivated with wheat and rapeseed in winter. In total, 80 ha of corn silo, 19.5 ha of wheat, and 20.5 ha of rapeseed are cultivated in the production system. According to the followed practice, two varieties of corn silo were planted to allow for a longer harvesting period. As can be seen from Table 3, approximately half of the area after harvesting is seeded with a winter crop (wheat or rapeseed).

Three tractors are assigned to the production system and used exclusively in the system (i.e., no hours spent for other operations or services to other production systems). The manpower is just family, and no price is stated because the manpower belongs to the farmer's income. It is possible, however, to assume a real manpower cost to estimate the profit for the farm. With the exception of the combine and forage harvester and the baling of the straw, the farmer owns the equipment required to carry out all operations. This machinery is hired as a service, and the corresponding costs are considered external costs. It should be noted that the capacity of the trailers/wagons is stated during the logistics operation because that operation depends on the moisture content of the crop and the material density (e.g., loose vs. pressed material, etc.). Only machines with a tank have a specific capacity because the product to be distributed is known.

For each operation, the production means (e.g., fertilising) and the production units of the crop were inserted when needed. Similar to the field operations, the logistics operations are carried out by defining the tractor and equipment used and the loads carried out during each trip. The yield per ha determines the number of trips per field and the working times.

3.1 MODEL RESULTS

As mentioned above, the web tool provides two types of output tables. The first is the average of each individual crop (3 output tables in total) and the second is the output for each individual production unit (10+5+5=20 output tables in total). The average of the corn silo crop is presented in Table 7, and the output for the wheat production unit in field 4 is presented in Table 8. Table 7 presents the average result for the corn silo crop from all the production units with this crop as provided by the web tool. Presented for each operation are the day of operation, as provided by the user, the area upon which the specific operation has been applied (in the second bracket), the tractor and machinery used, the type of the manpower and the calculated operational time per ha for labour. Table 9 provides the summarised results for all types of crops and production units.

An important aspect to be considered is the variability of the results between the different fields/production units. For the total expenses, the average total cost of corn silo was estimated at 28.95 €/t, with a standard deviation of 1.57 and a range of 4.34 €/t; the average total production and transport cost of wheat grain was estimated at 133.89 €/t, with a standard deviation of 5.25

and a range of 13.43 €/t; the cost of wheat straw was estimated at 47.82 €/t, with a standard deviation of 1.88 and a range of 4.8 €/t; and the average cost of rapeseed was estimated at 164.49 €/t, with a standard deviation of 6.46 and a range of 14.86 €/t. These variations are a result of the operational costs (both for field and transport operations). For corn silo, the variation is translated to 217 €/ha (assuming 50 t/ha yield) and demonstrates the importance of incorporating geographical variability of the production system, which diversifies the transport-operations cost, and field characteristics such as the soil conditions, which diversifies the field-operations cost. The diversification of average-estimated values would be even greater if different cultivation systems (e.g., reduced tillage) were adopted for the same crop in different production units.

4. CONCLUSIONS

A web-based tool for simulating the production, harvest, and out-of-field transport of biomass in multiple-crop production systems for feeding bio-energy plants was developed and demonstrated. The detailed consideration of the characteristics of the individual production units with regards to distance from associated facilities, soil conditions, machinery systems, and labour types can provide an accurate assessment of the system under consideration. The tool can also support decisions at different planning levels. By testing alternatives, the tool can support decisions on the strategic level (e.g., number and dimensioning of machines, machine capacity, crop selection, and labour requirements), the tactical level (e.g., fertiliser/chemical application plans, and labour budgets), and the operational level (operations specifications).

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