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AN OPTIMAL DYNAMIC DECISION MODEL FOR FOREST BIOMASS EXPLOITATION

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Abstract: A decision support system for forest biomass exploitation for energy supply is presented. The system allows supporting decisions on a finite time horizon, concerning the localization, sizing, and setting of a number of biomass-to-energy conversion plants in a small-medium region. The system is based on the formalization of an optimal decision problem stated with reference to a dynamic biomass model. In the proposed approach, geographic information system based techniques are integrated with mathematical programming methods yielding a comprehensive system which allows formalizing the problem, taking decisions, and evaluating their effects. The application to a real case study is considered. *Copyright © 2002 IFAC*

Keywords: Decision support systems, Renewable energy systems, Planning, Energy distribution, Information systems.

1. INTRODUCTION

An extensive literature reports biomass utilization experience in different territorial realities (among others, Ediger and Kentel, 1999; Martinot, 1998; Ushiyma, 1999; Basosi et al., 1999). Quantitative analysis about strategies for renewable energy sources from biomass has been performed either evaluating the potential resources of bioenergy in different kind of countries (Hall and Scrase, 1998) or matching the woody biomass demand and supply by the forest industries in Europe (Kuiper et al., 1998).
Decision support systems (DSS's) have been proposed to help biomass management for energy supply at a regional level. Nagel J. has recently proposed a methodology (Nagel. J., 2000a), tested in the state of Brandenburg, Germany (Nagel. J., 2000b), to determine an economic energy supply structure based on biomass. The problem is formulated as a mixed-integer linear optimization using the dynamical evaluation of economic efficiency, and with 1-0 conditions to solve the question whether to build or not a heating system, a heating plant or a co-generation plant. Nagel's works focus on many aspects such as the user typology that can benefit from biomass use for energy supply, on the dimension and typology of heating plants, and on the sensibility of the decision with respect to fuel costs. Among the conclusions of these two works, it was assessed that using biomass in individual plants is already economic for some consumers, although an attempt should be made to reduce the biogenic fuel prices. In addition, since biomass can help CO_2 emissions, an economy effort should be dedicated to establish CO_2 taxes or state subsidies for biomass-fired energy conversion plants or by changing the payment for electricity produced by biomass.
Another decision support system called AUHDSS for bioenergy application, with special reference to harvesting wood for energy from conventional forestry and short rotation forestry has been recently described. Such a system concerns the calculation of delivery cost of wood fuel from conventional forest in the UK (Mitchell C.P., 2000). In this work, an exhaustive review of topics related to the problem is given as well as an exhaustive list of computer models of bioenergy systems. Always from the same research group, other DSS's have been proposed for biomass management:

a) CDSS (Coppice Decision Support System), a spreadsheet model that can be used to model the costs of growing short rotation coppice under UK conditions (Mitchell, 1995);
b) CHDSS (Coppice Decision Support System), modeling the supply chain from the standing

coppice crop through harvesting, storage and transport (Mitchell, 2000).

The previous DSS's, as well as other models, were linked together to produce BITES, now presented in an extended spread-sheet based format called BEAM (Mitchell, 2000), that is an integrated biomass to electricity model.

The territorial evaluation, involving geographical (Noon et al, 1996, Graham et al., 2000), environmental (Nagel. J., 2000b) and socio-economic (Varela et al., 1999) characteristics of the region are also very important aspects in the decision modeling of biomass management. In this respect, Geographic Information Systems (GIS) based approaches have been recently proposed.

Noon and Daly, 1996, have proposed a GIS-based Biomass Resource Assessment, Version One, called BRAVO. BRAVO was defined as a computer-based DSS to assist the Tennessee Valley Authority in estimating the costs for supplying wood fuel to any one of its 12 coal-fired power plants. In BRAVO, the GIS platform allows the efficient analysis of transportation networks so that accurate estimates of hauling distances and costs can be determined. In a subsequent work (Graham et al., 2000) the previous work was extended under several aspects, one of which was the estimation of the costs and of the environmental implications of supplying specified amounts of energy crop feedstock across a state, considering where energy crops could be grown, the spatial variability in their yield, and transportation costs.

The aim of the present work is to show some basic results aiming at the development of a DSS approach to the regional exploitation of available biomasses for energy supply conversion taking the following decisions:

- where to install biomass energy conversion plants
- when to install biomass energy conversion plants
- how to schedule biomass collection, for the various parcels in the region
- sizing of each plant to be installed

on the basis of the following aspects:

- the environmental effects, such as the reduction of CO_2 emissions and the decrease of hydro-geologic and forest fire hazards due to a territorial improved care;
- the economic effects, such as the production of energy and the legislative benefits;
- the social effects, such as the improvement of employment in rural areas.

In this paper, a preliminary decision model is developed, which is mainly based on the second of the above aspects.

2. THE OPTIMAL DECISION PROBLEM

2.1 Problem description.

Suppose that a regional authority wants to evaluate the harvesting of forest biomass for energy production using combustion plants in a small medium territory (less than 1500 Km^2) mainly characterized by mountainous territory covered by spontaneous vegetation. The motivation of this decision is to join advantages given by an autonomous energy production, and environmental and social advantages, such as an improvement of the territory control that should be related to a reduction of forest fire risk, a reduction of CO_2 emission for energy production and an improvement of social and work activities in rural areas. The energy conversion plants are not present or partially only present in the territory.

Biomasses are present in the territory in different locations. In this work, $i=1,...,N$ parcels of different areas (approximately 2500 parcels, having average area about 0.6 square km) have been considered, each of them being characterized by a predominant biomass typology. These parcels have also different characteristics, that are, for example, different slope variability and human accessibility. In this territory, $k=1,...,K$ eligible locations for plants for energy conversion from biomasses are assumed to have been identified.

In any of such locations at most one plant can be set . Each plant is assumed to last for T_{life} years.

In the proposed model, the decisional variables, quoted in bold throughout this work, are time-dependent:

- $\mathbf{u}_t^i$ is the biomass quantity, in m^3/y, collected in the i-th parcel in the t-th time interval;
- $\mathbf{x}_t^i$ is the biomass quantity, in m^3, available for collection in the i-th parcel at the beginning of the interval t-th;
- $\boldsymbol{\varphi}_t^{ik}$ is the biomass quantity, in m^3/y, sent to the k-th plant from the i-th parcel, in the t-th interval;
- $\mathbf{y}_t^k$ is the time-to-live, in years, of a plant in position k a the beginning of the t-th interval, whose value can range between T_{life} (when a plant is set up) and 0;
- $\mathbf{CAP}^k$ is the production capacity, in MW, of the plant set in location k;
- $\boldsymbol{\delta}_t^k$ is a 0-1 variable whose value is 1 if a plant is installed at location k, at the beginning of the t-th interval, and 0 otherwise.

Each time interval is supposed to be equal to a year.

2.2 The cost function.

The cost function C (in €) to be minimized includes four components:

$$\boldsymbol{C} = -\boldsymbol{G} + \boldsymbol{C_P} + \boldsymbol{C_T} + \boldsymbol{C_C} \quad \textbf{(1)}$$

where:

- $\boldsymbol{G}$ is the profit from energy production,
- $\boldsymbol{C_P}$ represents the costs related to the plants (installing and maintenance),
- $\boldsymbol{C_T}$ represents the costs related to the biomass transportation, and
- $\boldsymbol{C_C}$ represents the costs related to the biomass collection.

Energy production profits

Assuming that all the plants have the same efficiency, the profit from energy production is given by:

$$G = \sum_{t=0}^{T-1} \sum_{i=1}^{N} \sum_{k=1}^{K} \varphi_t^{ik} \cdot C^i \qquad \textbf{(2)}$$

where C^i is the profit (€/m^3) coming from selling the energy produced using biomass of parcel *i*. Referring to a biomass-burn plant, the profit can be computed according to:

$$C_t^i = \frac{1}{f} HV^i \eta C_e \qquad \textbf{(3)}$$

where:

- HV^i is the heating value expressed in MJ/m^3 for the biomass type predominant in cell *i*
- η is the net efficiency of the energy conversion coefficient that is supposed equal for all plants
- f is a conversion parameter whose value is 3.6 MJ/kWh
- C_e (€/1kWh) is the profit obtained selling 1kWh of electricity

Plant costs

Plant costs are related to installation and maintenance of a plant. These costs can be evaluated taking into account fixed costs and variable costs, namely:

$$C_P = \sum_{t=0}^{T-1} \sum_{k=1}^{K} \left(CF_t^k + CV_t^k \cdot \mathbf{CAP}^k\right) \cdot sign\left(y_t^k\right) + \left(CFI_t^k + CVI_t^k \cdot \mathbf{CAP}^k\right) \cdot \boldsymbol{\delta}_t^k \qquad \textbf{(4)}$$

where:

- CF_t^k (€) and CFI_t^k (€) represent the fixed costs, for the k-th plant, for maintenance and installation, respectively;
- CV_t^k and CVI_t^k (€/MW) represent the coefficients of the variable costs, for maintenance and installation, respectively for the k-th plant;
- $sign\left(\mathbf{y}_t^k\right)$ is a function whose value is 1 when $\mathbf{y}_t^k$ is strictly positive, 0 when $\mathbf{y}_t^k$ is 0 (or negative). This function allows to include in cost (G) only those related to actually working plants.

Transportation costs

Transportation costs can be expressed as:

$$C_T = \sum_{t=0}^{T-1} \sum_{i=1}^{N} \sum_{k=1}^{K} C^{ik} \boldsymbol{\varphi}_t^{ik} \qquad \textbf{(5)}$$

where C^{ik} is the unitary transportation cost (assumed independent from t) from cell *i* to location *k*.

Collection costs

Collection costs can be expressed as:

$$C_C = \sum_{t=0}^{T-1} \sum_{i=1}^{N} \frac{\mathbf{u}_t^i}{L^i} C_u \qquad \textbf{(6)}$$

where:

- L^i is the biomass quantity collected in cell *i* by a worker in a year
- C_u is unit collection costs (which is assumed to be independent of the parcel and of the time interval).

The overall cost function to be minimized can then be expressed

$$C = \left\{ \begin{array}{l} -\sum_{t=0}^{T-1} \sum_{i=1}^{N} C^i \boldsymbol{\varphi}_t^{ik} + \\ \sum_{t=0}^{T-1} \sum_{k=1}^{K} \left(\left(CF_t^k + CV_t^k \mathbf{CAP}^k\right) \cdot sign\left(\mathbf{y}_t^k\right) + \right. \\ \left.(CFI_t^k + CVI_t^k \cdot \mathbf{CAP}^k) \cdot \boldsymbol{\delta}_t^k\right) + \\ + \sum_{t=0}^{T-1} \sum_{i=1}^{N} \sum_{k=1}^{K} C^{ik} \boldsymbol{\varphi}_t^{ik} + \sum_{t=0}^{T-1} \sum_{i=1}^{N} \frac{\mathbf{u}_t^i}{L^i} C_u \end{array} \right\} \qquad \textbf{(7)}$$

2.3 The problem constraints

The following constraints have to be introduced in the formalization of the problem.

Plant duration

Once a plant has been set, it is supposed to last for a given time-to-live T_{life}. To allow the life of a plant to last exactly for T years, it is necessary to introduce the following constraints.

$$\mathbf{y}_{t+1}^k = \boldsymbol{max}\left\{\mathbf{y}_t^k - 1, 0\right\} + \boldsymbol{\delta}_{t+1}^k T_{life} \qquad \textbf{(8)}$$

t=-1,…,T-2 k=1,…,K

where $\mathbf{y}_{-1}^k$ is the initial "state" of the k-th plant before the possible setting of a plant at time instant *t=0*.

Biomass dynamics

The quantity of biomass, which is present in a parcel, is a function of a biomass growth dynamics and of the quantity of biomass that is collected. The biomass growth is supposed to follow a non linear growth model similar to typical population systems (Berryman, 1981; Begon and Mortimer 1981), that is:

$$\dot{x} = b_0 x - b_1 x^2 - u$$

where values of b_0 and b_1 value are different for each type of biomass.

The above continuous-time model can be discretized as follows

$$\mathbf{x}(t + \Delta t) = [1 + \Delta t b_0]\mathbf{x}(t) - b_1 \Delta t \mathbf{x}^2(t) - \Delta t \mathbf{u}(t)$$

Thus, taking $\Delta t=1$, the following dynamic constraints can be introduced:

$$\mathbf{x}_{t+1}^i = (1 + b_{0,i})\mathbf{x}_t^i - b_{1,i}(\mathbf{x}_t^i)^2 - \mathbf{u}_t^i \qquad \textbf{(9)}$$

t=0,…(T-1) i=1,…,N

Limitations on biomass collection

For each cell, the overall quantity of biomass that can be collected on the whole time horizon is supposed to be limited, in relation to the initial biomass quantity x_0^i, by the following constraint.

$$\sum_{t=0}^{T-1} \mathbf{u}_t^i \le U_{MAX} x_0^i \tag{10}$$

i=1,...,N

In addition, the following constraint has to be fulfilled:

$$\mathbf{u}_t^i \le \alpha_i \cdot \mathbf{x}_t^i \tag{11}$$

i=1,...,N t=1,...,T-1

where α_i is a given parameter fixed.

Mass balance

The biomass flow coming out from a parcel (i=1,...,N) and that is sent to different plants (in location k, k=1,...,K) must be equal to the overall biomass collected in the parcel, that is

$$\sum_{k=1}^{K} \boldsymbol{\varphi}_t^{ik} = \mathbf{u}_\mathbf{t}^\mathbf{i} \tag{12}$$

i=1,...,N t=0,...,T-1

Biomass flow constraints

The biomass quantity entering a specific plant must be less or equal to the plant capacity. This can be represented by the following constraint:

$$\frac{1}{3600 \cdot 24 \cdot 365} \cdot \sum_{i=1}^{N} \boldsymbol{\varphi}_t^{ik} \cdot HV^i \le \mathbf{CAP}^k sign(\mathbf{y}_t^k)$$

k=1,...,K t=0,...,T-1

(13)

Production plant constraints

The plants are supposed to operate under a maximum and minimum production threshold constraint. This can be expressed imposing that each plant must produce at least CAPmin (in MW), and at most CAPmax (in MW).

$$\text{CAPmin} \le \mathbf{CAP}^k \le \text{CAPmax} \tag{14}$$

Minimum energy recovery

A constraint imposing that the quantity of energy produced through renewable sources must be at least equal to a fixed percentage of the power required by the considered area. Specifically, the constraint is:

$$\frac{1}{3600 \cdot 24 \cdot 365} \cdot \sum_{t=0}^{T-1} \sum_{k=1}^{K} \sum_{i=1}^{N} \boldsymbol{\varphi}_{\mathbf{ikt}} \cdot HV_i \cdot \eta \ge \chi \cdot E_t$$

(15)

where :

- E_t is the power required for the considered area;
- χ is a parameter that indicates how much, at least, of the necessary energy must be obtained by biomass exploitation.

2.4 Solving the problem

The problem consists in the minimization of (7) subjected to constraint (8:15). It is a non linear mixed-integer optimization problem. Then, its solution requires the use of software packages (such as Lingo©) to obtain optimal or even feasible solutions. Computational experience has been made by solving such a problem in relation to the case study described in the following sections.

3. SYSTEM IMPLEMENTATION

A system allowing experts to plan the biomass exploitation in a region according to the previous optimization model has been implemented. This system can be classified as an Environmental Decision Support System (EDSS) (Rizzoli and Young, 1997). To support the decision, the EDSS is based on three modules:

– the GIS based interface for the characterization of the problem and for the computation of the parameters involved in the formulation of the problem;
– the database where data characterizing the problem are stored;
– the optimization module.

3.1 GIS based interface module

To define the problem from a geographical point of view, the experts can view the territory in a GIS oriented interface (fig.1). The territory is divided in parcels, characterized by an associated type of biomass.
As a first step, the experts can customize their problem, planning eligible forests for biomass collection and sites to set the energy conversion plants. By default, the system appoints as eligible all the parcels. However, the experts are allowed to exclude those parcels that they do not intend to consider for harvesting in any case (for example, because they are hardly reachable, or environmentally protected), or to add other biomass collection sites, such as for example biomass deriving from agriculture/industrial production. In addition, the experts can define the eligible sites where the set up of a plant will be evaluated.

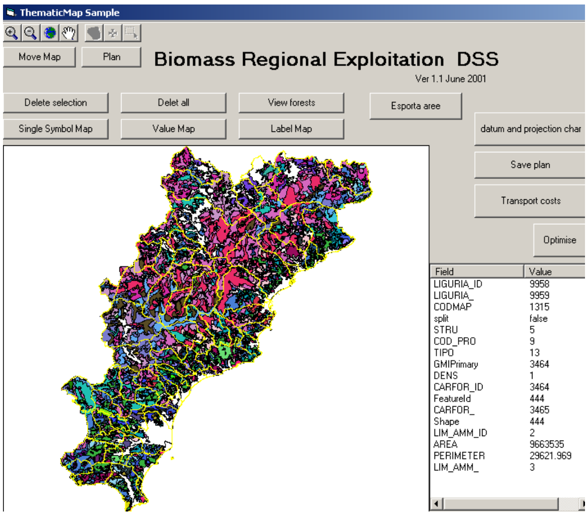

Fig. 1. The GIS application interface. This module allows to plan the scenario and to call the optimization procedure. The region shown in the picture is the Savona district, on part of which the DSS has been tested.

As a second step, some important characteristics of the system are computed:

- the productivity of each parcel can be manually entered in the system or computed as a function of the area of the parcel, of some important characteristics such as for example the mean and deviation standard of slope of the parcel, and of the type of biomass present in it;
- the travel costs between each eligible parcel and each eligible plant are computed using GIS functionalities;

As a third step, the optimization procedure is called. When the optimization procedure ends, the output of the system is shown on the map, in relation to the definition of the parcels on which it is convenient harvesting, and the definition of the number of plants, their location and sizing that are optimal from a cost point of view.

3.2 The biomass collection planning database module

For a suitable management of the information, the data planned in the GIS module and the results deriving from the optimization module are stored in a relational database.

3.3 The optimization module

The optimization module has been developed according to the model described in sections 2.1-2.4. The optimization module has been defined using Lingo© 6.0, by Lindo System. Communication with the database is managed by a proper ODBC (Open DataBase Connectivity) interface, while the optimization module is called within the MS Visual Basic 6.0 program by a specific Lingo component.

4. APPLICATION TO A CASE STUDY

The system has been applied to the consortium of municipalities in the mountain region of Val Bormida (Savona district). This region is covered for almost all its area (about 500 Kmq) by natural forest vegetation (mostly homogeneous hardwood forest). In this preliminary approach, this area has been divided in five parcels. Three possible sites for biomass-to-energy conversion plants have been taken into account. The optimization problem has been implemented on a time interval of T=3 yrs. The parcels and the possible location for plants considered in this work are shown in Figure 2.

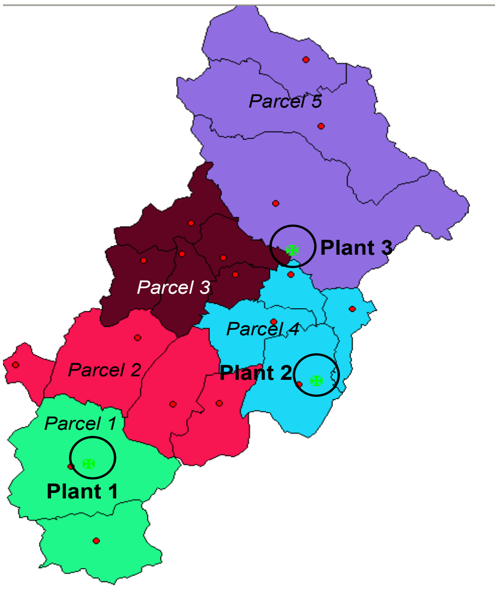

Fig. 2.

Results obtained are reported in the following tables. Specifically, table1 reports plants capacity (if the plant is installed in the specific site).

Table 1 Plants capacity

Plants(k)	$\mathbf{CAP}^k$
k=1	10
k=2	0
k=3	10

Table 2 provides the information relevant to the times at which plants are installed.

Table 2 Installation of the plants

Time(year)	δ_t^1	δ_t^2	δ_t^3
t=1	1	0	1
t=2	0	0	0
t=3	0	0	0

Finally, the harvested biomass is reported in Table 3.

Table 3 Harvested biomass

	$\mathbf{u}_1^i$	$\mathbf{u}_2^i$	$\mathbf{u}_3^i$
Parcel 1	65100	62242	59624
Parcel 2	62300	59565	57060
Parcel 3	8120	8052	7987

Parcel 4	51800	49526	47443
Parcel 5	94372	101160	107379

The overall optimal cost for this strategy corresponds to 3.8 M€.

5. CONCLUSIONS AND FUTURE DIRECTIONS

In this paper, an optimal decision problem over time, relevant to biomass exploitation for energy generation has been modeled and the application to a case study has been provided. The problem formulation is based on a dynamic model representing the evaluation over time of the biomass over the various parcels. The cost to be optimized is relevant to collection, transportation and plant costs, and benefit from energy selling has been considered. Several constraints have been introduced to represent technical issues to be taken into account. On this basis, the structure of a Decision Support System has been described, which includes a GIS-based module that has to be used to have access to all information which is needed for the problem formulation.

Further research on this topic will be devoted to the development and the calibration of a more accurate model of the biomass dynamics, when should take into account the stochastic aspects of the considered system. In such a case, the application of optimal control approaches should replace an approach based on the application of mathematical programming.

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