International Congress on Environmental Modelling and Software

3rd International Congress on Environmental Modelling and Software - Burlington, Vermont, USA - July 2006

Jul 1st, 12:00 AM

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R. Minciardi

M. Robba

Roberto Sacile

F. Frombo

Fulvia Rosso

Minciardi, R.; Robba, M.; Sacile, Roberto; Frombo, F.; and Rosso, Fulvia, "A Decision Support System for energy production from renewable resources: logistics aspects of sustainable forest biomass collection" (2006). *International Congress on Environmental Modelling and Software*. 325.
https://scholarsarchive.byu.edu/iemssconference/2006/all/325

A Decision Support System for energy production from renewable resources: logistics aspects of sustainable forest biomass collection

Riccardo Minciardi[a,b], Michela Robba[a,b,*], Roberto Sacile[a,b], Francesco Frombo[a,b] ,Fulvia Rosso[a]
[a]CIMA-Interuniversity Center of Research in Environmental Monitoring, Italy
[b]DIST-Department of Communication, Computer, and System Sciences, Italy
*Corresponding author: michela.robba@unige.it

Abstract: The consequences of the use of traditional fossil fuels has led, in the last years, the European Union to promote and encourage the development and the use of renewable energies rather than the traditional ones. Energy production from forest biomass does not involve the CO_2 increase in the atmosphere, contributing in this way to the duties assumed by the European Community during the International Conference of Kyoto (1997). The developed DSS, that is a generalization and the further research activity presented in a previous work by the same authors (Freppaz et al. [2004]), is based on the integration of Geographic Information Systems tools, a relational database, and decision models (in terms of decision variables, objectives, and constraints). Specifically, two decision models have been created in order to face two sustainability verifications. The first one regards the planning of biomass collection and transport considering the biomass as a constant over time. In this case, the objective is to find the forest parcels from where it is convenient to collect biomass, for certain fixed plant sizes, and establish the quantity to take from each of them and to send to a specific plant, considering the geographical characteristics and the legislative constraints. This problem corresponds to a static decision model. The second decision model has a dynamic structure and it considers the biomass collection planning over five years, on the basis of a preliminary plant size, found solving the previous mathematical programming problem. The structure of the dynamic decision model is strictly connected with the growth model of the trees that are present in the different forest parcels.
A user friendly interface is used to link the optimization models, the GIS, and the metadata necessary for the problem solution.

***Keywords**:* Decision Support Systems, Biomass, Energy Production, Logistics, Optimization.

1. INTRODUCTION

In the last years, the European Union promoted and encouraged the development and the use of renewable energies rather than the traditional fossil fuels. Energy production from biomass exploitation does not involve the CO_2 increase in the atmosphere, as a matter of fact the same quantity of CO_2 produced during the energy generation process is taken away from the atmosphere thanks to vegetation growing. This cyclic process results in a net inflow of CO_2 in the atmosphere equal to zero, contributing to the duties assumed by the EU during the International Conference of Kyoto (1997). In the recent literature, several papers can be found about Environmental Decision Support Systems (EDSS), their definition, characteristics, complexity, implementation, etc. One of the most recent papers on this subject is presented by Matthies et al. [2005] states that an EDSS often consists of various coupled environmental models, databases and assessment tools, which are integrated under a graphical user interface (GUI), often realized by using spatial data management functionalities provided by geographical information systems (GIS). Denzer [2005] states that Environmental Information Systems (EIS) and EDSS are major building blocks in environmental management and science today. They have specific characteristics that distinguish them from standard information systems, e.g. information complexity in time and space or uncompleteness or fuzzyness of data items. Decision support systems (DSS’s) have been proposed to help biomass management for energy supply at a regional level. Nagel [2000a; 2000b] has proposed a methodology to determine an economic energy supply structure based on biomass. These works focus on many aspects such as the user typology that can benefit from biomass use, 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. GIS-based approaches have been recently proposed to promote geographical, environmental, and socio-economic evaluations at regional scale. Noon and Daly [1996] have proposed a DSS GIS-based called BRAVO (Biomass Resource Assessment, Version One) to assist the Tennessee Valley Authority in estimating the costs for supplying wood fuel coal-fired power plants. The GIS platform allows the efficient analysis of transportation networks and accurate estimates distances and costs. Forest biomass exploitation for energy production should be helpful for increasing the value of the territory through a specific attention to the forest ecosystem, to the environmental impact, and to social, logistic, and economical issues. The DSS developed in the present work, based on a previous study by Freppaz et al. [2004], integrates GIS tools, relational database, and decision models (in terms of decision variables, objectives, and constraints).

The research activity started thanks to the collaboration with the local authorities of Savona Province and Val Bormida Mountain Community that had the exigency of defining (and/or evaluating) strategies for the use of woody biomass for energy production, and imposed the requirements and the issues that the DSS should have contained. The present paper, that concerns sustainability of a given plant is suitable also for Private enterprises. In fact, the work started from a collaboration with a small medium enterprise (working on the energy sector) on the Savona territory that wanted to make a proposal for a plant in Mallare (Savona Province, Italy), and had to prepare the study for the environmental impact assessment to be evaluated by local authorities.

In this paper, two decision models have been created. The first one regards the planning of biomass collection and transport considering the biomass as a constant over time. In this case, the objective is to find the forest parcels from where it is convenient to collect biomass, for certain fixed plant sizes, and establish the quantity to take from each of them and to send to a specific plant, considering the geographical characteristics and the legislative constraints. This problem corresponds to a static decision model. The second decision model has a dynamic structure and it considers the biomass collection planning over five years, on the basis of a preliminary plant size, found solving the previous static mathematical programming problem. The structure of the dynamic decision model is connected with the growth model of the trees that are present in the different forest parcels. However, the aim of this paper is not the one of presenting and discussing a calibration of the forest growth model but the one of presenting decision models for planning and management purposes, able to integrate different aspects. The benefits of the DSS lie in the coupling of GIS and decision models that should help decision makers in finding strategies and in exploring the useful information about the considered territory. From a scientific point of view, it represents an evolution (respect to the previous published work by the same authors) in terms of new decision variables, objectives and constraints. A case study is presented, and the obtained results discussed.

2. 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 EDSS, see Rizzoli and Young, [1997]. To support the decisions, the EDSS is based on three modules:

- the GIS-based interface for the characterization of the problem and for the computation of the parameters;
- the database with the data characterizing the problem;
- the optimization module.

To define the problem 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 or to add other biomass collection sites (agricultural or industrial production). In addition, the experts can define the eligible sites where the set up of a plant will be evaluated. After optimization procedure the output of the DSS, as location of harvesting parcels, number, location, and size of plants related to an economic point of view, is shown on the map. 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. Communication with the database is managed by a proper Open DataBase Connectivity (ODBC) interface, while the optimization module is called within the MS Visual Basic 6.0 program by a specific Lingo component.

3. THE DECISION MODEL

The developed DSS has the main objective to define the sustainability of different plant capacity scenarios on a territory inside the Savona Province. The formalization of the static and the dynamic optimization problem is here presented in two different sub-sections.

3.1 Formalization of the static optimization problem

The cost function, C [€], that should be minimized (which decision variables are the biomass quantities u_i [$m^3\ year^{-1}$] collected in the i-th parcel) is composed by two terms:

$$C = C_{TR}\sum_{i=1}^{N} d_i MV_i u_i + \sum_{i=1}^{N} Cr_i MV_i u_i \qquad (1)$$

where:

- C_{TR} [€ $Km^{-1}Kg^{-1}$] is the unit transportation cost;
- d_i [Km] is the distance of the i-th parcel from the plant;
- MV_i [$Kg\ m^{-3}$] is biomass density for every parcel;
- Cr_i [$€\ Kg^{-1}$] is the unit collection cost for parcel i.

Such costs are strongly influenced from the characteristics of the territory: every parcel has its collection costs, depending on the viability conditions, the presence of infrastructures, the terrain accessibility and slope. In order to take into account such aspects, unit collection costs have been grouped and defined considering four levels about biomass collection: from an easy level to a non-practicable level. The problem formalization also includes the definition of different typologies of constraints: limits on the biomass collection and on the material entering the plant.

The possibility of biomass collection on a territory must respect the forest regulations inside the Forest Plans which contains all the guidelines about the methods of forest management, treatment, and use. From the analysis of such documents and data, it is possible to consider a medium “cut turnover system” for coppice and high forest equal to 20 and 100 years, respectively, corresponding to a percentage of annual cutting of 5% and 1%. In every parcel, known the biomass quantity x_i, in m^3, the quantity that can be collected is

$$u_i \le \alpha_i \cdot x_i \qquad i=1,\dots,N \qquad (2)$$

$$u_i \ge 0 \qquad i=1,\dots,N \qquad (3)$$

where α_i is the maximum percentage of biomass quantity that is fixed by law. These coefficients assume a value equal to 0.05 for coppice and 0.01 for high forest, according to the local regulations.

The biomass quantity entering a specific plant should be equal to the plant capacity. This, can be represented by the following constraint

$$\frac{PCI}{3600 \cdot 8000}\sum_{i=1}^{N} MV_i u_i = \frac{\boldsymbol{CAP}}{\eta_e} \qquad (4)$$

where:

- PCI is the low heating value assumed constant for not-treated biomasses, assuming a medium humidity of 30-35%;
- η_e is the plant electric energy efficiency;
- 8000 are the functioning hours in a year;
- 3600 is a conversion factor (hours in seconds).

Such formalized problem is a linear programming problem and can be solved by commonly used optimization tools.

3.2 Formalization of the dynamic optimization problem

Referring to the previous plant characteristics and considering the biomass growth dynamic, the objective is now to plan collection in the first five years of the plant.

This means that the terms of the static model previously described will be function of the parcels and of time discrete values. Then, the state variables x_i^t [$m^3 \cdot ha^{-1}$] will appear in order to indicate the available biomass in parcel i at time t. Apart this, the two optimization problems do not present substantial differences in their formulation. For this reason and also to lower the technical focus of the paper, the equations are here omitted. Instead, attention is pointed on a new equation that represents the state of biomass quantity during its growth. This dynamics is here represented as a second order polynomial and recalls the simplest form used in population dynamics. Similar equations are used by Bernetti [1998], and Berryman [1981]. The discretized (taking a time interval discretization $\Delta t=1$) equation is

$$x_{t+1}^i = (1+b_{0,i})x_t^i - b_{1,i}(x_t^i)^2 - u_t^i$$
$$t=0,\dots(T-1) \qquad i=1,\dots,N \qquad (5)$$

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

4. THE CASE STUDY

The DSS has been applied to a territory inside the Savona Province to evaluate the environmental impact and the sustainability, in a specific area, of a plant producing electric energy. The study area is inside a part of territory belonging to two different Mountain Communities: Val Bormida and Val Pollupice. These areas have a high tree density index (respect to Italian tree densities), and have some industrial activities linked to wood-use and that produce scraps that can be burnt in the plant.

The first step has been the one of analyzing the territory that should be exploited to collect biomasses. Through GIS tools the parcels centroids have been identified, and different data have been associated (area, slope, biomass quantity and growth parameters). The total study area is about 32000 hectares, however a part of forest territory can't be exploited because of the presence of legislative constraints (natural parks and protected area), and so the remaining area is about 20000 hectares. These remaining parcels are reported in Figure 1.

Figure 1. Forest parcels that can be used for the case study.

Besides legislative aspects, considering the real possibility of biomass collection the following parcels have been neglected too:

- private properties that could not be included because of the lack of permission from the owner;
- slope more that 50%;
- distance from major roads greater than 100 meters;
- areas of bio-naturalistic importance;
- areas characterized by forest fires and by hydro geological risk.

The total area available from biomass exploitation was $5.6 \cdot 10^3$ hectares and a biomass quantity equal to $8.6 \cdot 10^5$ m^3.

The main typologies of forest biomass present on the territory are chestnut, beech, conifer and durmast. Other kinds of biomasses should be added as inputs of the model because of the agreements among the local industries:

- scraps from wood industries;
- scraps from pruning of public urban vegetation, pallets, and cratings;
- chestnut from a wood trader in Val Bormida.

The biomass coming from the industrial scraps is used entirely (100%), while forest biomasses are used according to the legislative constraints previously discussed.

In Table 1, the values of parameters b_0 and b_1 present in equation (5) for every biomass typology are reported. These values have been calculated on the basis of the available data for the case study, and they are different from those reported by Bernetti in his work.

Biomass	b_o	b_1
Beech	2,73*10^{-2}	7*10^{-5}
Chestnut	5,21*10^{-2}	1*10^{-4}
Conifer	4,69*10^{-2}	6*10^{-5}
Durmast	1,127*10^{-1}	3*10^{-4}

Table 1. Values of parameters present in equation (5) found for the case study.

Figure 2 shows the growth curves specific for each type of forest biomass. It is important to note that Val Bormida's forest parcels are characterized by different structures of forest stand growth. Old and mature populations constituted the greater part, while the remaining part presented a normal distribution due to management treatments executed during the time. Biomass growth parameters were obtained by interpolation of data coming from forest stands with normal-age distribution. The main simplification of this model is that growing stocks, calculated on the basis of these parameters, were also applied to old parcels, without a normal distribution of plants in age-classes.

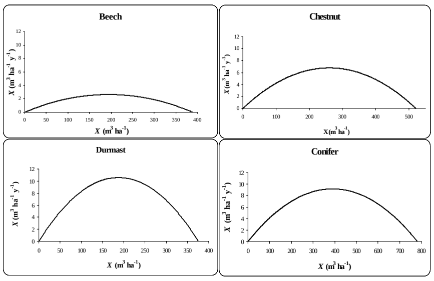

Figure 2. The growth model for the biomass typologies in the considered territory.

Due to this lack of specific data regarding age for the case study, these models give the possibility to have an initial idea of the forest biomass behavior over time in the territory. Of course, when better data will be available the models will be calibrated over all the parcels. The advantage of having a DSS is also that of analyzing results faster when new data and information are known. In this case, changing the values of the parameters in Table 1.

4.1 Results

The optimization problem has been implemented through the use of an optimization software (Lingo 8.0, Lindo Systems Inc.). First of all, the static optimization problem has been solved for different plant capacities. For each run, the optimal value of the decision variables and of the objective function that respect the formalized constraints are found. Incrementing CAP each time, if the available biomass is sufficient, the optimization problem is feasible, otherwise the Lingo software finds a "not feasible solution". This sensitivity analysis is then performed till the capacity that is not sustainable (that is, till when the optimization software gives a feasible solution). In the following, results for possible plant capacities (CAP = 1 MW, 2 MW, 3 MW, etc.) are reported. The DSS has furnished feasible solutions till a plant capacity of 6 MW, without reaching the 7 MW capacity. With the only aim of testing the decision model, the sensitivity analysis has been performed for values of CAP that do not correspond to real installed plants. It can be seen that the model is sustainable till CAP=6.42 MW. Of course, CAP=6.42 MW cannot be a real plant capacity. This value should be observed only as a result of the sensitivity analysis of the proposed decision model. Table 2 reports the objective function values for different CAP.

CAP [MW]	Objective function [€]
1	0
2	0
3	65805
4	401101
5	815201
6	1480792
6,42	1958196

Table 2. Optimal solution for different CAP

In Figure 3, a cost-benefit analysis for different plant capacities, comparing the costs curve (in which installation fixed costs are also included) with the benefits line, coming from the sales of produced energy, is shown. It comes out that a reasonable benefit is obtained for a plant with capacity between 4 and 5 MW.

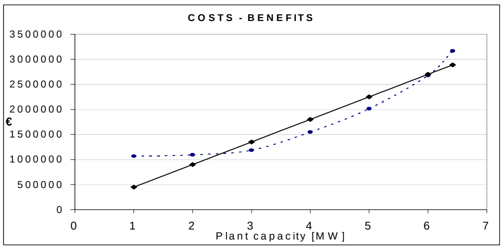

Figure 3. Cost benefits analysis.

According to these results and to the experts, further analysis have then been performed on a plant with a capacity of 5 MW. Specifically, in Table 3 is reported the optimal solution for a plant capacity equal to 5 MW. The used forest parcels are the 50% (in number of 192) of the total forest parcels (374).

Used biomass	
MW	5
m^3	86418
%Industrial scraps	100%
% Used forest biomass	1,7%
Parcels number	192

Table 3. Optimal solution for CAP = 5 MW

With the aim of describing in a complete way the obtained results and the sustainability of the plant, a calculation of the produced emissions, and in particular the ones produced by the vehicles used for the transport, has been performed.

In order to move the biomass from the single forest parcel to the plant, camions able to take 20 tonns of material, diesel, have been considered. Once the number of necessary vehicles has been calculated, and known the distance among each parcel and the plant (calculated through GIS capabilities), it has been possible to calculate the pollutant emissions in the atmosphere, due to transport operations. In function of the necessary vehicles, and then in function of the plant capacities, the emissions values of SO_2, NO_X, dust, CO, HC, and CO_2 are reported in Table 4.

MW	SO_2	NO_x	DUST	HC	CO	CO_2
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	92390	101629	10676	22584	101629	8212439
4	152719	167991	17648	37331	167991	13585051
5	310197	341217	35845	75826	341217	27573077
6	466704	513375	53930	114083	513375	41484821
6.42	554249	609674	64047	135483	609674	49266567

Table 4. Emissions of the various pollutants for the different plant capacities.

Another aspect that should be mentioned when analyzing the impacts on the territory is the traffic induced by the collection and the transport of biomasses. Knowing the road run that links every parcel to the plant and having calculated the number of vehicles that are necessary to take the material, the yearly flows of vehicles for every main road has been calculated. Finally, the dynamic decision model has been applied. From the previous results, CAP =5 MW has been considered. The primary objective of this decision problem is to define the collection activity in the first five years of the plant life, highlighting the yearly costs. In particular, the costs and the exploited parcels change every year, while a power of 5 MW is assured (with constraint (4)). The dynamic model influences directly the biomass collection because of constraint (2) that, depending on the biomass quantity present in the parcel (constraint (5)) allows (or doesn't allow) biomass collection in a specific parcel.

The communes from which is collected most are Mallare and Calice Ligure. As an example, in Figure 4, the collected biomass in these communes is shown over the first five years.

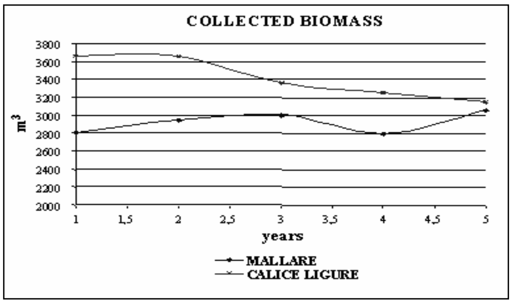

Figure 4. Collected biomass in Mallare and Calice Ligure for the first five years (CAP = 5 MW)

5. CONCLUSIONS

In this work, the problem of defining an optimal exploitation plan of the biomass for a consortium of municipalities in an Italian mountain region has been considered. The main innovation proposed in this work is relevant to the definition of a comprehensive quantitative approach, based on a DSS that can suggest actions and policies to boost biomass utilization. Specifically, in this approach, it is possible to plan biomass exploitation in a region, sizing the plants and verifying the performances of the overall system.

Future developments, of the presented DSS, that the authors of the paper are currently developing, regard mainly the forest system, and the energy production processes. In the first case, the "work in progress" regard a more accurate formalization of the forest growth model, a quantification (for different forest ages) of the CO_2 absorption by the forest in connection to the growth model, and the modeling of humidity variation in the vegetation. Temporal carbon dynamic stocks and flows, for a variety of forestry and agroforestry systems, will be assessed.

In the second case, the authors are adding more typologies of energy production processes (pyrolisis, gasification) in connection to different typologies of biomasses to be burnt. Then, great efforts will be dedicated to a cost-benefits analysis of the dryer plant, that reducing humidity should increase the fuel heating value. In particular, it is necessary to model the drying process and to define, in time, the flow of materials entering and going out from the dryer, in connection with the logistics aspects of biomass collection and transport. The presented activities are being developed in a project, funded by Liguria Region and some enterprises present in the territory (that are directly involved in the development of the DSS), that has the main scope of developing a laboratory of research for the use of renewable resources for energy production.

6. ACKNOWLEDGEMENTS

The authors would like to thank Liguria Region and the enterprises co-financing the project "Laboratory for the energy production from Renewable Resources" for the data collection and for the exchange of knowledge necessary for the development of the DSS

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