Sustainable biomass power plant location in the Italian Emilia-Romagna region

MASSIMILIANO CATTAFI, MARCO GAVANELLI
ENDIF Università di Ferrara
MICHELA MILANO
DEIS Università di Bologna
PAOLO CAGNOLI
ARPA Emilia-Romagna

Biomass power plants are very promising for reducing carbon oxides emissions, because they provide energy with a carbon neutral process. Biomass comes from trees and vegetables, so they provide a renewable type of energy. However, biomass plants location, along with their provisioning basins, are heavily regulated by economical aspects, often without careful consideration of their environmental footprint. For example, some Italian biomass plants import from overseas palm-tree oil that is economically convenient. However, the energy consumed for the oil transportation is definitely greater than the energy produced by the palm-tree oil burning. In this way biomass power plants turn out to be environmentally inefficient, even if they produce renewable energy.

We propose an Integer Linear Programming approach for defining the energy and cost efficient biomass plant location along with the corresponding provisioning basin. In addition, the model enables to evaluate existing plants and their energy and cost efficiency.

Our study is based on real data gathered in the Emilia-Romagna region of Italy.

Finally, this optimization tool is just a small part of a wider perspective that is aimed to define decision support tools for the improvement of regional planning and its precise strategic environmental assessment.

Categories and Subject Descriptors: I.2.1 [**Artificial Intelligence**]: Applications and Expert Systems; G.2.1 [**Discrete Mathematics**]: Combinatorics—*Combinatorial algorithms*; J.2 [**Computer Applications**]: Physical sciences and engineering—*Earth and atmospheric sciences*

General Terms: Algorithms, Experimentation, Performance, Economics

Additional Key Words and Phrases: Computational sustainability, facility location

1. INTRODUCTION

Although the end of fossil fuels seems postponed to a midterm future, the search for new energy sources is recently having a new boost: after decades of warnings from the environmental experts, citizens and governements start to realize that we cannot continue polluting our planet indefinitely. Nowadays the main concern is not running

Authors' addresses: M. Cattafi and M. Gavanelli (corresponding author), ENDIF - Via Saragat 1 - 44122 Ferrara (Italy).
M. Milano, DEIS, Viale Risorgimento 2 - 40136 Bologna (Italy).
P. Cagnoli, ARPA - Sede Direzione Tecnica - Largo Caduti del Lavoro, 6 - 40122 Bologna, (Italy).

DOI 10.1145/0000000.0000000 http://doi.acm.org/10.1145/0000000.0000000

out of oil, but running out of *air* to burn it: carbon oxides are known to increase the greenhouse effect widely recognized as the main responsible for climate change. As former OPEC minister Ahmed Zaki Yamani said, *"The Stone Age did not come to an end because we had a lack of stones, and the oil age will not come to an end because we have a lack of oil"*.

In the search for reducing carbon oxides emissions, biomass-powered power plants are very promising, because they provide energy with a carbon neutral process. Biomass comes from trees and vegetables that in their life converted carbon dioxide to oxygen, and burning them simply returns part of the energy they got from sunlight, so it gives a renewable type of energy. Also, for countries that mainly rely on imported energy, biomass power may mean an economy less dependant on the price of oil. For these reasons, energy from biomass is currently receiving substantial governmental funding.

On the other hand, unluckily, building a biomass plant does not necessarily imply any improved sustainability, as the plant is inserted into an environment, with complex interrelations, including production of fumes, the need for refrigeration, transport of the biomass from the production sites to the power plant, and so on. Without taking into consideration such aspects, the project is quickly doomed to failure.

Even more importantly, there are economic aspects that rule the whole life of the biomass plant. For example, in Italy energy producers that use renewable sources have the right to sell energy to the energy provider (ENEL) at a price higher than the market price [CIP6 1992]. Since energy selling price is higher than the market price, the plant manager can afford to buy biomasses at higher prices than the market price. This helps the development of new renewable power plants, but on the other hand may lure the manager to produce energy with low-cost fuel, like palm-tree oil imported from overseas. Unfortunately, the energy needed to transport the fuel overseas is much higher than the energy actually produced by burning it in the biomass plant. Nevertheless, it gives good revenue to the plant manager. However, even excluding these extreme situations, it may actually happen that the transport of the biomass to the plant consumes more energy than that produced in the plant. Again, the reason is economic: the producers of biomass may be lured by the high revenues to carry biomass from far-away production sites, or with highly polluting and/or energy demanding trucks.

One of the issues is the combinatorial nature of the problem. A good location of the biomass plant is of vital importance for the economic survival of the project, and it includes solving complex location and transportation problems. Many works in the literature deal with this aspect [Freppaz et al. 2003; Bruglieri and Liberti 2008; Reche-López et al. 2009].

The second issue is the sustainability of the project, and this is affected by more subtle aspects. In this work, we explicitly address the biomass plant location problem with the aim of maximizing the sustainability, starting from real world data gathered in the Emilia-Romagna region of Italy.

This work is only a part of a wider picture: we aim at developing a decision support and optimization tool for the Emilia Romagna regional planning and its strategic environmental assessment. The biomass plant location is an important aspect to be taken into account in regional planning. The tool proposed in this paper helps both the regional planning and its strategic environmental assessment by defining the optimal sustainable biomass provisioning basin and by assessing already installed plants. Before going into the details of the specific biomass power plant location problem, we contextualize it in the wider picture.

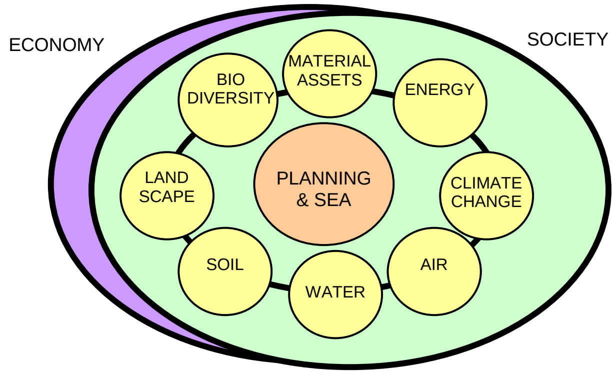

Fig. 1. The Universe of Regional Planning and SEA

1.1. Regional Planning and Strategic Environmental Assessment

The energy and cost-efficient biomass plant optimal location proposed in this paper is just a small part of a wider picture whose long term goal is the design and implementation of decision support and optimization tools for the Regional Planning and its Strategic Environmental Assessment (SEA). It involves problems related to a number of different yet correlated areas as shown in Figure 1. A comprehensive decision support system for regional planning and SEA should be able to optimize decisions in all these fields while at the moment only qualitative aspects are considered and manually evaluated.

Regional planning is the science of efficient placement of land use activities and infrastructures for the sustainable growth of a region. Regional plans are classified into *types*; the SEA is legally required for eleven types of plans (namely Agriculture, Forest, Fishing, Energy, Industry, Transport, Waste, Water, Telecommunication, Tourism, Urban and Environmental plans). Each plan defines activities that should be carried out during the plan implementation. Activities are roughly divided into six types: infrastructures and plants; buildings and land use transformations; resource extraction; modifications of hydraulic regime; industrial transformations; environmental management.

Before any implementation, these plans have to be environmentally assessed, under the *Strategic Environmental Assessment Directive*. SEA is a method for incorporating environmental considerations into policies, plans and programs, and it is prescribed by the European Union policy.

The importance of applying decision support systems to regional planning derives from the huge economic and environmental impact that wrong decisions could have. One of the instruments used for assessing a regional plan in Emilia Romagna are the so called *coaxial matrices*, that are a development of the network method [Sorensen and Moss 1973]. They define dependencies between the activities contained in a plan and positive and negative *impacts* (also called *pressures*) on the environment and the dependencies between the impacts and environmental receptors. A plan basically defines the so called *magnitude* of each activity.

The coaxial matrices are currently used by environmental experts that **manually evaluate a single, already defined, plan**. A manual evaluation of alternatives and *what-if* queries are very difficult to consider. In addition, planning is now carried out without a rigorous consideration of environmental aspects contained in the coaxial matrices.

Our aim is to design and implement a decision support and optimization tool for the strategic environmental assessment and for the regional planning. For this purpose, we have developed a logic-based system [Gavanelli et al. 2010] that embeds the coaxial matrices; the system can be used both by the environmental expert to assess an already defined plan, and by the politicians to evaluate different scenarios and optimize regional planning decisions. The current environmental assessment is based on qualitative measures of the impact on environmental receptors.

A more in-depth insight on quantitative measures would be extremely helpful to build and assess a regional plan. For example, in the energy plan the environmental expert finds information of this kind: *two biomass power plants are planned to be built in the next two years*. On the basis of this high level information, only a rough expected impact on environmental receptors can be computed. If the decision support system linked to the SEA enables the planner and the environmental expert to optimally locate the power plant so as to minimize the environmental negative pressure, the coaxial matrices can be populated with precise data and the environmental assessment becomes more transparent.

In this paper we describe the design and implementation of one component of the overall quantitative regional planning and SEA picture. This component is an optimization tool which is able to find the optimal energy efficient biomass plant location, together with corresponding biomass provisioning plan. It can also be used to evaluate existing plants/provisioning plans with respect to their energy balance. In addition, the tool can help in deciding whether or not to open a biomass power plant in a given location (possibly converting an old industrial infrastructure to a biomass power plant).

All these activities are inserted in the wider frame of the quantitative Strategic Environmental Assessment that is subject of current research.

The rest of the article is organized as follows. We first define the problem, and show the collected data from the Emilia-Romagna region. Then, in Section 3, we define a Mixed-Integer Linear Programming (MILP) model that optimally locates one or more biomass power plants in a devised area of the region, optimizing in particular the ecological sustainability of the project. In Section 4 we study the complexity of the problem. We show the results obtained from the MILP model in Section 5. We discuss related work in Section 6 and conclude with Section 7.

2. PROBLEM DESCRIPTION

Biomass power plants may be aimed at obtaining energy from a variety of different fuels: from garbage, to forest/sawmill residues, to manure [Thomas 2008]. In this work, we address the problem of the optimal location of a biomass plant that uses wood obtained from forests. This does not mean deforestation, as wood can come from dead trees, branches, tree stumps, etc., as well as from *selection cutting*, that is the practice of removing mature timber to improve the timber stand. In sustainable forest management, a selection cutting criterion requires to cut less than the yearly produced biomass.

Before building a power plant, one should get the required authorisations from the regional bureaus. As stated earlier, this includes an evaluation of the environmental impact of the power plant. Various locations are not acceptable for a power plant, due to various reasons that come from geological information, regulations, statistics on pollution, types of crops in the surrounding fields, etc. Other locations could be acceptable but raise some issues that need further investigation before the project can be accepted.

To define disallowed areas, and areas requiring further investigations, the environmental experts of the Emilia-Romagna region reported into a table the possible inter-

Sensitivity theme	Wind powered generators	Biomass plants	Hydroelectric plants
Vulnerable waters	yes	maybe	maybe
Airports	no	maybe	maybe
Archaeology sites	maybe	maybe	maybe
Military regions	no	no	no
Unstable terrain	no	no	no
Rivers	no	no	yes
Natural parks	no	no	yes
Water wells	yes	no	maybe
...			

Table I. Excerpt from the interference matrix *"sensitivity themes vs. power plants"* in the Emilia-Romagna region

ferences between various types of power plants with *sensitivity themes*, i.e., types of areas that may be sensitive to such a plant. Table I is an excerpt of such a table.

For each theme, the required information are gathered into a map, given as a shapefile of a Geographical Information System (GIS). Shapefiles can include points, line segments, or polygons representing areas with common characteristics. Through a GIS software, one can overlap shapefiles as layers of a map. In this way, by overlapping all the maps of themes incompatible with some power plant type, the map of incompatibility for a given plant type can be generated: it is the set of areas in which there is at least one layer (theme) that forbids such plant (see Figure 2). From this process a set of feasible locations is identified.

We consider the problem of locating a plant that uses biomass obtained from forests. Biomass is then transported to the power plant; we suppose that the transport is through roads. The regional agency kindly provided us with the GIS map of roads as well as the shapefile of forests. The shapefile of roads is a set of line segments: each road segment is a straight line segment connecting two points, given with longitude and latitude. A road is then a sequence of segments; the length of each segment is between 6 and 20 metres.

We built a graph containing as nodes all points from the roads' shapefile. Two nodes are connected if there is a straight road segment connecting the two.

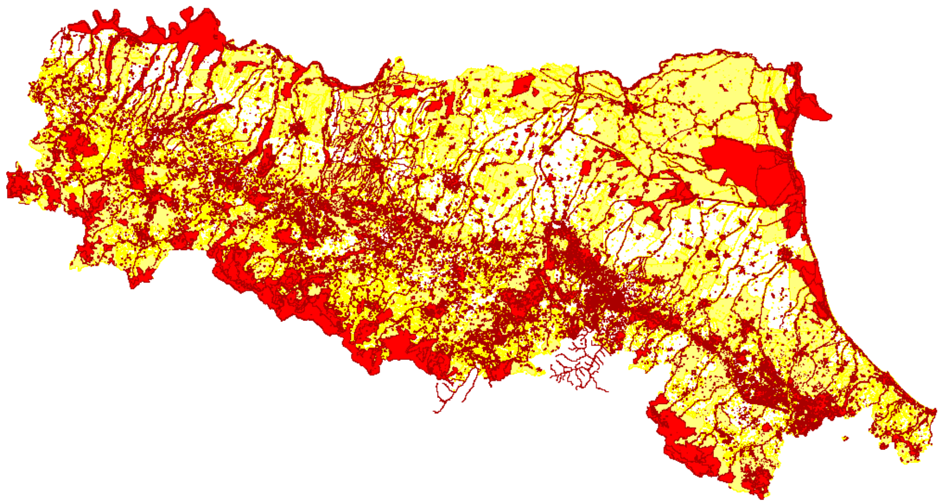

Fig. 2. Map of incompatibility for biomass power plants in the Emilia-Romagna region.

We assume that the biomass plants will be built in close proximity to some road, and that biomass is collected near a road, to allow for a convenient transportation of biomass material from the collection point to the plant. In our model, only the nodes of the obtained graph are possible biomass plant locations. On the other hand, there is no point in selecting the actual positioning with a precision of 20 metres, so we use a sampling of the nodes based on proximity.

In the graph, each node is labelled as *red* if the node is internal in a polygon incompatible with biomass plants, it is *green* if it is a biomass collection point, it is *white* otherwise. Each arc is labelled with its length. Thus, candidate positions for the power plants are the white nodes, biomass is collected at green nodes, and transported to the power plants by following paths in the graph.

In the following, we propose a Mixed-Integer Linear Programming (MILP) model to address the plant location problem.

3. A MILP MODEL

The MILP model used to address the given problem relies on a problem representation given as a graph. Starting from the general graph described earlier, we produce a smaller bipartite graph, that connects possible locations of the biomass power plants to the location of the forests. Each arc is labelled with the shortest path length between the two nodes; the (shortest path) distance between two nodes i and j is called d_{ij}, and it is a parameter (it is a known constant).

We have an array of unknowns P that represents the possible locations of the plants: the element p_i can be 0 or 1; it is 1 iff we build a power plant in node i. We suppose we want to build in the devised region a number of plants which belongs to the fixed range Min^p to Max^p ; we ensure this fact through the constraint

$$Min^p \leq \sum_{i=1}^{N^P} p_i \leq Max^p. \tag{1}$$

We also have N^F forest nodes, i.e., nodes from which the owners can collect wood that can be used to produce energy in the biomass plant. As said earlier, wood can come from forest residues (such as dead trees, branches, tree stumps, etc.) or from *selection cutting*. Each forest node i has a production of wood $prod_i$ that cannot be exceeded, because the quantity of wood removed from a region should not exceed the yearly produced biomass, in order to have a sustainable process. We have a matrix of unknowns C_{ij} that links power plant nodes with forest nodes. Element C_{ij} gives the quantity of wood that is provided from forest node i to plant node j. The constraints include that the total quantity of wood provided by a forest node i does not exceed its carry capacity:

$$\forall i \in \{1..N^F\} \qquad \sum_{j=1}^{N^P} C_{ij} \leq prod_i.$$

Each power plant has a minimal quantity of wood $mindemand$ it must receive in order to be operative; otherwise there is no point in installing such a plant

$$\forall j \in \{1..N^P\} \qquad \sum_{i=1}^{N^F} C_{ij} \geq p_j \cdot mindemand.$$

Symmetrically, there is a maximum quantity of wood a power plant can accept:

$$\forall j \in \{1..N^P\}, \qquad \sum_{i=1}^{N^F} C_{ij} \leq p_j \cdot maxdemand.$$

Note that this constraint also imposes that one cannot provide wood to a plant that is not installed.

Finally, we have economic parameters and sustainability parameters.

We assume that owners can collect residual wood from the nearby forests, and will transport them to one plant (usually the closest one), in exchange for money. Now, if the revenue is lower than the supply cost, then there will be no deal, so we need to take into account two important parameters: the unit price paid for the wood, $Price^{wood}$, and the unit supply cost. The supply cost for the forest owner includes a collection cost and a transport cost. We assume the collection cost is proportional to the quantity of collected wood (although it could depend on many factors, like slope and extension of the wood). For the transport cost, we consider a parameter $Cost^{trans}$, that represents the cost of transporting one unit of wood for a distance of one unit. So, we have that plant j can receive wood from forest node i only if it is economically advantageous to collect and transport wood from i to j. The transport cost is proportional to the quantity and to the distance through constant $Cost^{trans}$, i.e. the cost to transport a quantity C_{ij} from node i to node j is

$$d_{ij} \cdot Cost^{trans} \cdot C_{ij}, \tag{2}$$

so the supply cost becomes

$$Cost^{collect} \cdot C_{ij} + d_{ij} \cdot Cost^{trans} \cdot C_{ij}. \tag{3}$$

The revenue for the seller of wood is proportional to the quantity, so if she provides C_{ij} units of wood, she will get a revenue of

$$Price^{wood} \cdot C_{ij} \tag{4}$$

from which she expects some minimum profit

$$Profit^{wood} \cdot C_{ij}, \tag{5}$$

for example, we can have that $Profit^{wood} = 0.2 \cdot Price^{wood}$: it is a constant parameter explaining that the seller will not sell the biomass if her profit is below 20% the total price of the biomass. Combining equations (3), (4) and (5) we get that the net revenue is acceptable iff

$$Cost^{collect} + d_{ij} \cdot Cost^{trans} + Profit^{wood} \leq Price^{wood}$$

is satisfied. If it is not, then we impose that $C_{ij} = 0$.

From a sustainability viewpoint, the aim is that the whole system generated by the new plant produces renewable energy (at the net of consumed energy). The system contains the plant, as well as the forest owners collecting wood and transporting it to the plant, so we must ensure that the energy spent for the transport and for building the plant does not overpass that produced by the wood in the plant.

The wood transport is usually performed by means of some vehicle of the wood provider, which can be efficient or not. We fix an average efficiency parameter, and call E^{fuel} the energy provided by the fuel necessary to move one unit of wood for one distance unit. On the other hand, we have that one unit of wood provides energy E^{wood}. Also, we have to consider that building a plant requires itself an energy investment, and such aspect should be taken into account in the energy balance: we will consider this contribute in a term γ, that will be detailed in the following. Thus the objective function considering transportation and sustainability issues is

$$max(f) = \sum_{j=1}^{N^P} \sum_{i=1}^{N^F} C_{ij} \left(E^{wood} - d_{ij} E^{fuel} \right) - \gamma. \tag{6}$$

The energy required to build a new plant depends mainly on its location and its size. The contribution for the location can be considered as a coefficient α_i associated to each node $i \in \{1..N^P\}$ in the graph that is candidate to host a plant. The size of the plant can be given, e.g., in terms of its input power. In our case, the power the plant gets as input is the energy of biomass it receives divided by the time the plant is operative:

$$\mathcal{P}_j = \left(\sum_{i=1}^{N^F} C_{ij} \cdot E^{wood} \right) / T^{op}.$$

The relation between the size of the plant and the energy required to build it, as reported in the documents of the European Commission [2006], is given by

$$\mathcal{E} = \mathcal{E}^0 \cdot \left(\frac{\mathcal{P}}{\mathcal{P}^0} \right)^s$$

where $\mathcal{E}^0$ is the energy required to build a plant of reference size $\mathcal{P}^0$ (in some location with $\alpha = 1$). The scale factor s goes usually from 0.5 to 1. Clearly, in the extreme case of $s = 1$ we have a linear relation: building two plants of 1MW or one plant of 2MW has exactly the same energy requirement[1]; instead, when $s < 1$ we can exploit economy of

[1]Provided that the locations are comparable, i.e., they have the same coefficient α.

scale for the plant. So, knowing the energy $\mathcal{E}^0$ required to build a plant of size $\mathcal{P}^0$, the energy required to build a plant in node j is given by the non-linear relation

$$\mathcal{E}_j = \alpha_j \mathcal{E}^0 \left(\frac{\mathcal{P}_j}{\mathcal{P}^0}\right)^s = \alpha_j \mathcal{E}^0 \left(\frac{\sum_{i=1}^{N^F} C_{ij} \cdot E^{wood}}{\mathcal{P}^0 T^{op}}\right)^s. \tag{7}$$

Equation (7) provides the total energy required to build a new plant in node j. Such energy should be considered in the objective function, as we want the whole system to produce energy; however, the other terms in Equation (6) represent the produced energy and the cost of transport *per year*, so to add up the two terms we need to amortize the total energy $\mathcal{E}_j$ during the lifespan of the plant. We simply divide $\mathcal{E}_j$ for the average number of years a plant is productive, T_j^{life}, and obtain as new objective function:

$$max(f) = \sum_{j=1}^{N^P} \left(\sum_{i=1}^{N^F} C_{ij}(E^{wood} - d_{ij}E^{fuel}) - p_j \frac{\alpha_j \mathcal{E}^0}{T_j^{life}} \left(\frac{\sum_{i=1}^{N^F} C_{ij} \cdot E^{wood}}{\mathcal{P}^0 T^{op}}\right)^s \right) \tag{8}$$

Such objective function is nonlinear and, since the exponent s is at most 1, the term in Equation (7) is concave (whenever $s < 1$).

In order to fit the nonlinear function in the MILP model, we approximate it with a piecewise linear function.

Given a (possibly nonlinear) function $y = g(x)$, we sample the curve g in k points $x_1, \ldots, x_k$; the piecewise linear approximation $y' = g'(x) \simeq g(x)$ is defined as

$$\begin{aligned} x &= \textstyle\sum_{i=1}^{k} \lambda_i \cdot x_i \\ y' &= \textstyle\sum_{i=1}^{k} \lambda_i \cdot y_i \end{aligned}$$

where $\lambda_i \in [0..1]$ are new continuous variables subject to the constraints

$$\textstyle\sum_{i=1}^{k} \lambda_i = 1$$
At most two of the λ_i can be nonzero
The two nonzero λ_i must be adjacent

Clearly the last two conditions are not linear; they can be stated in a MILP model introducing new integer 0-1 variables, but there exists a more efficient option. In many MILP solvers, one can declare $(\lambda_1, \ldots, \lambda_k)$ as a Special Order Set of type 2 (SOS2) [Beale and Tomlin 1970], and the solver will exploit this information for efficient branching heuristics.

It should be noticed that, for the sake of sustainability, the problem cannot be just formulated under an economical point of view, as the market prices of biomass and fuel needed for transportation do not reflect the respective energy potential. This is caused by a number of reasons, the most relevant of which is that institutions such as the European Union or the regional government issue economical incentives for the use of the former (e.g. trying to push entrepreneurs towards renewable energy). For this reason it is possible that the economic net revenue for the plant is positive even if the whole system, including the transport chain and all the rest which is needed in order to make the plant work, actually *consumes* energy at the net.

4. COMPLEXITY

We show that the problem addressed in this paper is NP-hard, even in the case in which there are no restrictions on the plants' capacity.

THEOREM 4.1. *The uncapacitated biomass plant location problem is NP-hard.*

PROOF. We prove NP-hardness by reduction from the Facility Location Problem. A Facility Location Problem is defined as the 4-tuple $\langle D, F, f, d\rangle$, where

— D is a set of clients
— F is a set of potential facility locations
— d is a function $d : D \times F \to R^+$ representing the distance between clients and possible facility locations
— f is a function $f : F \to R^+$ representing the cost of opening a new facility

The objective is to find the set $S \subseteq F$ that minimizes

$$\sum_{i \in S} f_i + \sum_{j \in D} (min_{i \in S} d_{ij}) \tag{9}$$

Given an instance of the facility location, we build the following biomass plant location problem:

— the set of forest nodes is equal to the set of clients D
— the possible positions of the biomass plant are the potential facility locations
— the energy required to build a plant is independent of the size of the plant ($s = 0$)
— the cost of opening a new biomass plant coincides with function f $\left(f_i = \frac{\alpha_j \mathcal{E}^0}{T_j^{life}}\right)$
— the distance between forest and plant nodes coincides with the distance function d
— the number of plants is not constrained (Min^p=0 and $Max^p = |F|$)
— all forest nodes produce a unit of biomass ($\forall i \in \{1..N^F\}, prod_i = 1$)
— $Cost^{collect} = 0$, $Cost^{trans} = 0$, $Price^{wood}$ is any number greater than zero
— E^{wood} is a sufficiently high number ($E^{wood} > E^{fuel} \cdot max_{i=1..N^F, j=1..N^P}(d_{ij})$)
— the biomass plant does not have (constraining) minimum and maximum capacity ($mindemand = 0$, $maxdemand = \sum_{i=1}^{N^F} prod_i$)

Now, we decompose the objective function (8) into the terms:

$$max(f) = \sum_{j=1}^{N^P} f_j \cdot p_j + \sum_{i=1}^{N^F} \sum_{j=1}^{N^P} C_{ij} E^{wood} - \sum_{i=1}^{N^F} \sum_{j=1}^{N^P} C_{ij} d_{ij} E^{fuel}$$

The first term is the same as in Equation (9). From the definition of E^{wood}, we have that the coefficient $(E^{wood} - d_{ij} E^{fuel})$ in the objective function (8) is always positive. Since there are no limits on the capacity of a plant, all the available biomass can be collected, so in an optimal solution of the biomass plant placement problem the second term is the constant $\sum_{i=1}^{N^F} \sum_{j=1}^{N^P} C_{ij} E^{wood} = \sum_{i=1}^{N^F} prod_i$. From this observation descends immediately that the optimal solution of the biomass plant placement problem provides an optimal solution of the Facility Location Problem, if every forest node provides biomass only to one plant.

Let us suppose that, in the optimal solution of the biomass plant placement problem, one forest node i provides biomass to two plants, let us call them j_1 and j_2. In this case, the two plants must be at the same distance from node i ($d_{ij_1} = d_{ij_2}$), because otherwise all the biomass could be carried to the closest facility (as we do not have capacity constraints), providing a better value of the objective function (which contradicts the fact that such solution is optimal). Since the two plants are at the same distance, we can move all the available biomass to one of them, say j_1, without changing the value of the objective function. We can apply this method to all forest nodes that serve more than one plant and obtain an optimal solution of the Facility Location Problem. □

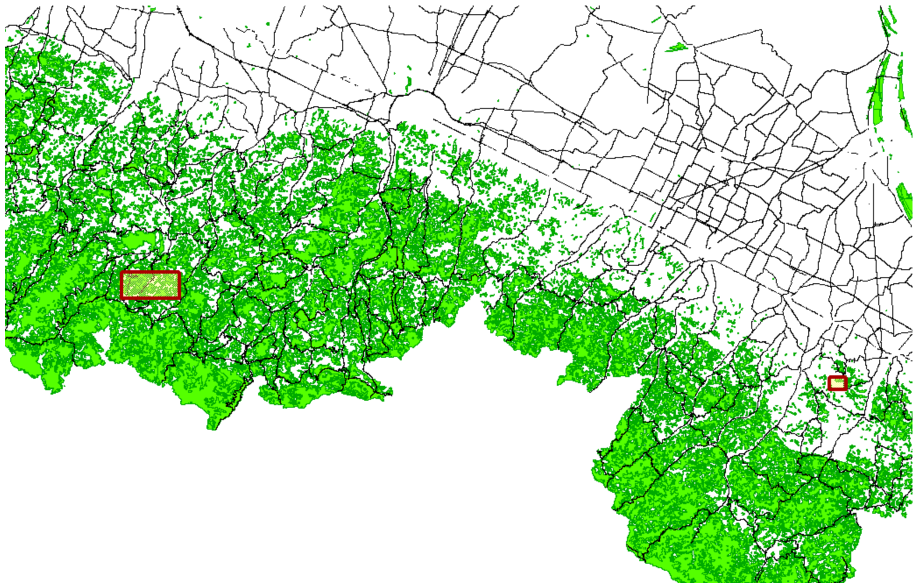

Fig. 3. The areas used in our tests

5. EXPERIMENTAL RESULTS

We experimented our MILP model on two subregions of the Emilia-Romagna region, delimited by rectangles in Figure 3.

In Figures 4 and 5 the detailed views are shown of, respectively, the western and eastern areas, with the available roads (the main roads are thicker), the forest areas (solid filled surfaces) and areas where biomass plant location is impossible (hatched).

The two areas were selected with different characteristics, in order to study our approach in different scenarios. The western area has large availability of forests, and it is wider than the eastern area; this area could support the presence of many power plants, which can make the problem difficult to solve computationally. The eastern area is more restricted, and it contains less forest nodes, so in this case transport issues are particularly relevant, as biomass may have to be collected from many dispersed forests.

We ran a series of experiments on those areas.

In Figures 4 and 5 results are shown of optimal placement without considering energy cost of plant construction. The squares are the optimal placements of plants found by the model and the different sizes show the associated biomass demand and energy production. In Figure 5 the spot on one of the forest areas shows, for example, one of the biomass supply points associated to the linked plant in the optimal provisioning plan, while the cross shows the placement of one plant as prescribed by the solution obtained choosing as the objective function the maximization of profit rather than the energy balance.

In both areas the goal was to place a number of plants not greater than 5 and whose production had to be more than 0.2 MW but less than 1 MW (thus adopting the point of view of distributed power generation).

The considered values for energy parameters are $E^{wood} = 15000 MJ/tonne$ for biomass and $E^{fuel} = 7 MJ/km$ for fuel (we are considering fuel consumption being 0.1 lt/km for a load of one tonne). The market price for biomass has beed set to

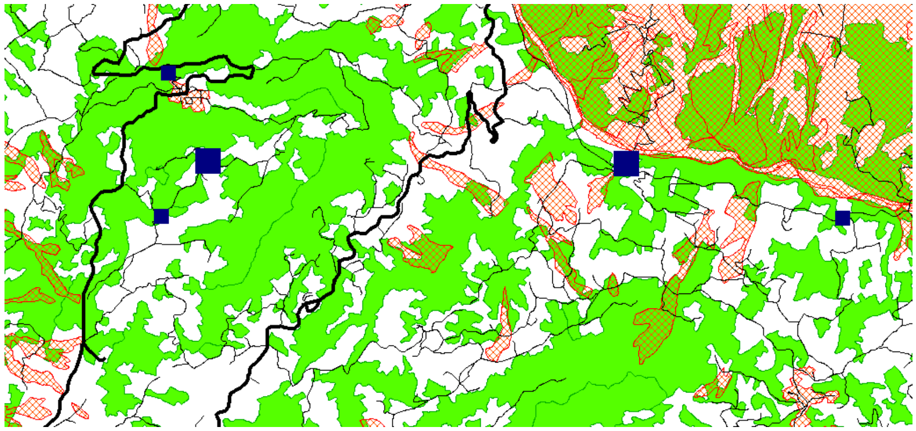

Fig. 4. Detail of the western area. Squares mark optimal placements of plants without considering plant construction energy investment. Different sizes show the associated biomass demand and energy production.

$Price^{wood} = 30 euros/tonne$, and collection cost to $Cost^{collect} = 25 euros/tonne$. We assume the biomass seller accepts as a minimum profit 15% of $Price^{wood}$ ($Profit^{wood} = 4.5 euros$) for selling biomass and $Cost^{trans} = 0.2 euros/km$. All these parameters are of course affected by some variability: different kinds of wood have different E^{wood}, fuel consumption and E^{fuel} depend on the means of transport (small vans, big trucks, tractors, etc.), the collection cost depends on the characteristics of the collection area, and the price of biomass and the expected profit follow market dynamics. All the values of the parameters were estimated by the environmental experts of the regional agency, based on their experience in the environmental impact evaluation and, whenever possible, on officially available data. For parameters with high variability they suggested to take the average value.

The western area is mapped on approximately 300 nodes, while the eastern counts approximately 100. Results were obtained in 10 minutes in the former case and 5 seconds in the latter one, using a 2 GHz Core 2 Duo processor.

The total net energy produced by the plants in the two optimal configurations is respectively 88500 GJ and and 16800 GJ for the western and eastern areas, while the total energy necessary for the transportation of the biomass to the power plant is, respectively 96133 MJ and 4707 MJ. In both cases, the net produced energy is positive, which shows that the optimal placement reached its objective. On the other hand, when choosing to maximize the profit in the eastern area, while the produced energy is the same, the energy necessary for the transportation of the biomass rises to 16793 MJ so while the energy balance keeps being positive, it is less favourable.

In Figures 6 and 7 results of placement are shown considering also the energy investment for plant construction. The environmental experts of the regional agency suggested that, in order to build a reference plant of $\mathcal{P}^0 = 0.5MW$ the required energy is $\mathcal{E}^0 = 45TJ$; the exponent in Equation 7 has value $s = 0.8$, and the average lifetime of a plant is $T^{life} = 25$ years. The total net energy produced by the plants in the two optimal configurations is respectively 78995 GJ and and 14858 GJ for the western and eastern areas.

It is interesting to study the total net energy produced by the whole system varying the number of biomass power plants. In Figure 8, we show the results for the eastern area. After a sharp rise of the curve, due to the fact that only one plant cannot use all the available biomass, the curve decreases slowly, with an optimum number of

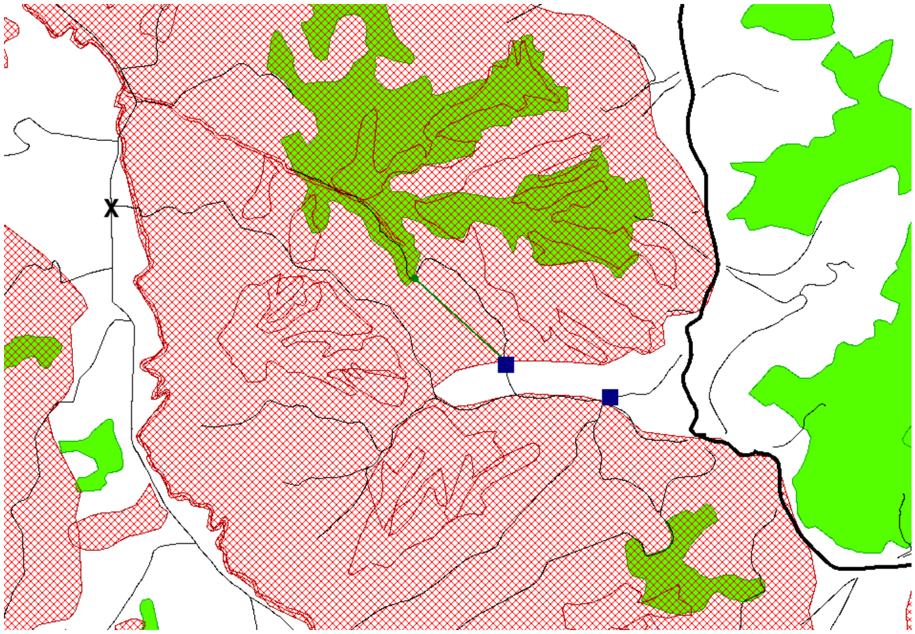

Fig. 5. Detail of the eastern area. Squares mark optimal placements of plants without considering plant construction energy investment. Different sizes show the associated biomass demand and energy production. Forest area spot linked to plant shows one of the biomass supply points in the optimal provisioning plan. The cross shows the placement of one plant when the goal is maximizing profit.

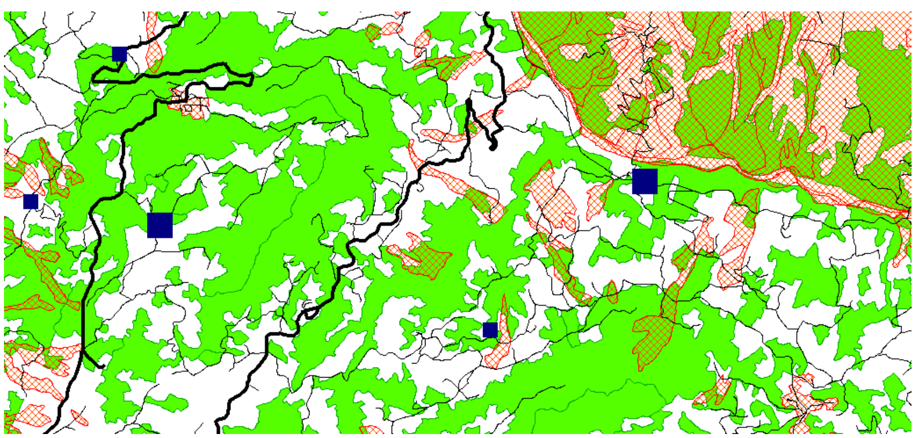

Fig. 6. Detail of the western area. Squares mark optimal placements of plants without considering plant construction energy investment. Different sizes show the associated biomass demand and energy production.

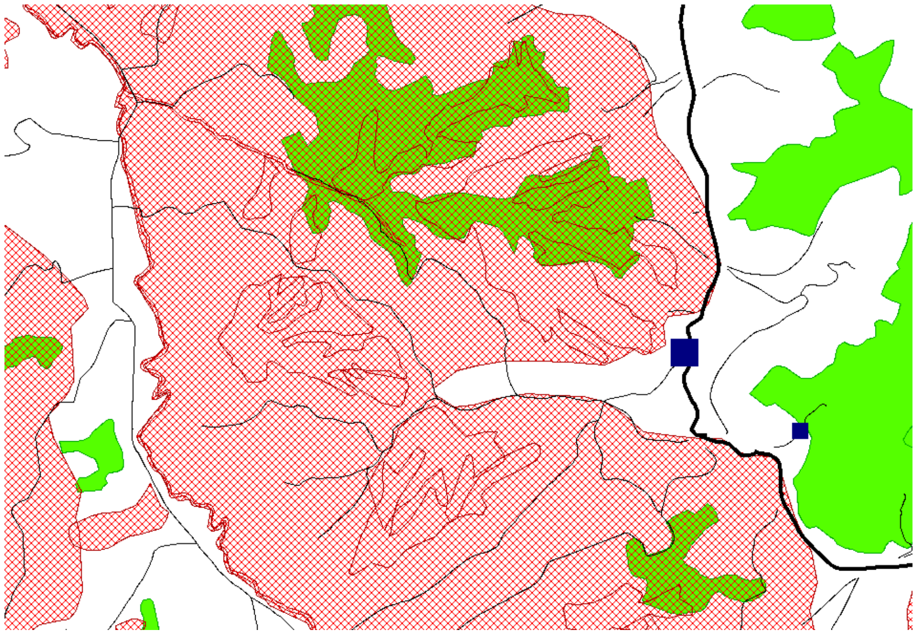

Fig. 7. Detail of the eastern area. Squares mark optimal placements of plants considering plant construction energy investment. Different sizes show the associated biomass demand and energy production.

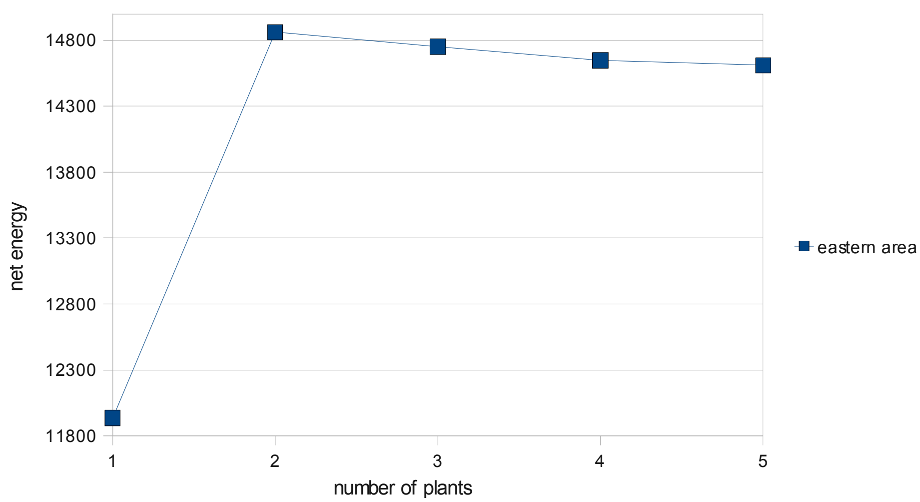

Fig. 8. Net energy (GJ) produced in the eastern area varying the number of installed power plants.

plants equal to 2. This effect shows that there are opportunities given by economies of scale: the configuration with two plants (including a bigger one) is more rewarding than building 5 small ones. It is worth noting that with a coarser model, that does not consider the non-linearities in Equation (7), such effect would not appear.

However, it is worth noting that the production of energy, and, as a consequence, the sustainability of the defined choice, depends on the value of the parameters. As said earlier, we took average values provided by the experts for the transport cost $Cost^{trans}$, the energy generated by the fuel E^{fuel}, as well as the price and energy for biomass (respectively, $Price^{wood}$ and E^{wood}); however, we know that the price of fuel has high variability, that depends on the market, the rising demand of developing countries, the taxation level, etc. The energy of fuel is more stable, but still it depends on the type of fuel available in the devised area, and in the Emilia-Romagna region there are at least four types of widely distributed fuels (petrol, diesel fuel, methane, and propane). We wanted to assess the sustainability of the power plant and its provisioning system, and find out if, for some combinations of the parameters, the sustainability of the system drops.

In Figure 9, we show the variation of the net energy production varying the other parameters, computed in the eastern area. It emerges that the important parameters are actually the ratios between the parameters. The biomass / fuel cost ratio expresses the relation between the biomass price the plant manager pays for one load of biomass ($Price^{wood}$), and the transport cost for one unit of length ($Cost^{trans}$). The biomass / fuel energy ratio expresses the relation between the energy potential contained in one load of biomass (E^{wood}) and the energy used to transport the biomass for one unit of length (E^{fuel}).

In the abscissa of the graph of Figure 9, we have the ratio $Price^{wood}/Cost^{trans}$. Higher prices for biomass allow forest owners to collect biomass not only from the very close woods but also from some more distant ones, thus influencing in a positive way the objective function at the beginning. In fact, Figure 9 shows that the net produced energy initially increases as the ratio $Price^{wood}/Cost^{trans}$ grows. However, at some point a saturation occurs, that can be due to various factors: for instance the limit on the total power production may be reached (maximum number of plants times the maximum energy produced by each plant).

On the z axis the ratio between energies E^{wood}/E^{fuel} is plotted; we have fixed the energy produced by biomass E^{wood} and varied the E^{fuel} energy necessary to transport a unit of biomass for a unit of distance. In this way, we can take into account both different types of fuel, and different types of transport media (e.g., small or big trucks) with varying efficiency (e.g., with old or new engine types). As expected, reducing the energy required for transportation increases the net produced energy up to a saturation and, vice-versa, the increase in the amount of energy used to transport one load of biomass causes a decrease in the maximum net energy that can be produced. It is worth noting that there is a threshold in which the system, as a whole, starts *consuming* energy, instead of producing it. Note, however, that sometimes even if the net produced energy is negative, the net revenue for the various actors (the plant management and the forest owners) is not zero: the system consumes energy but still produces *money*. This is the worst possible situation from a sustainability viewpoint: the biomass plant pollutes the local region with fumes and, at the same time, it consumes energy.

But there is also an even worse risk, much more subtle: if the environmental assessment of the plant (and, most importantly, of the whole system) is done after building the plant, workers will become frustrated, and stakeholders will think that investing in the green economy is futile.

It is of utmost importance to identify these possible situations as early as possible, before the plants are built, and local authorities should intervene before the required authorisations are given. During the environmental assessment (see Section 1.1) these possible problems should be identified, possibly with an expert system to support decisions. This work should be seen as one of the various elements in the wider picture of strategic environmental assessment.

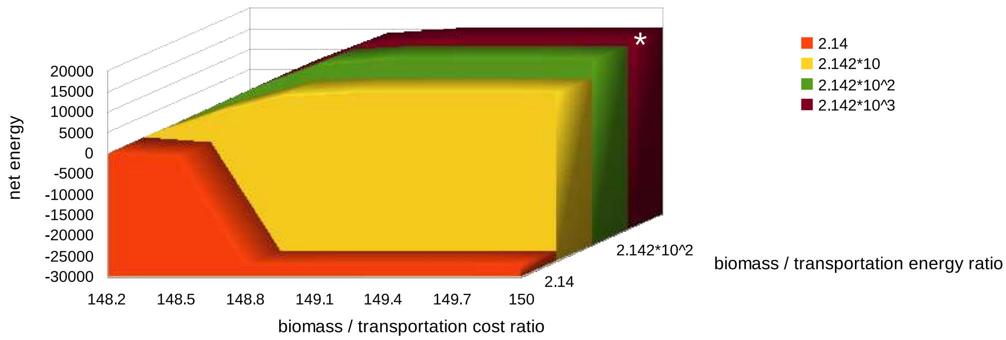

Fig. 9. Net energy (GJ) as a function of (dimensionless) ratios of biomass and transportation related parameters. On x axis, ratio of cost of a biomass load and cost to move the load for one length unit. On z axis, ratio of energy of a biomass load and energy to move the load for one length unit. (*) indicates the parameter context of previous experiments.

6. RELATED WORK

The problem of biomass power plant location is widely investigated in the literature with the aim of defining optimal positioning with respect to economic aspects.

Bruglieri and Liberti [2008] study the problem of running and planning a biomass-based production process. The aim is to optimize a process in which various plants process material, and exchange the products. For example, there can be a fermentation/distillation plant taking as input cane or beetroots and providing as output some type of alcohol, that can be input for another plant. In the optimization of running of the biomass-based process, the authors suppose a fixed amount of various output commodities is required, and minimize the operation costs (i.e., the cost of supplying plants with input commodities, transportation costs and processing costs). The authors also consider the planning of the production process, that includes deciding where and what type of processing plants one should install in various available locations. Our aim is more on the sustainability aspects rather than on the economic ones. Our model includes the energy required for building the power plant, that is approximated with a piecewise linear function of the plant capacity.

Reche-López et al. [2009] consider the problem of placing a biomass power plant. They compare various metaheuristics (Simulated Annealing, Tabu Search, Genetic Algorithms and Particle Swarm Optimization) to find a near-optimal positioning of the biomass plant. They consider only economic factors to decide the biomass plant placement, i.e., their objective is to find the placement that gives maximum revenue. Another incomplete iterative GIS-based approach for the identification of candidate power plants is described in [Voivontas et al. 2001]. It identifies possible restrictions to the biomass power plant location and iteratively identifies potential locations along with the cultivated areas needed for the biomass collection. In this paper, we adopted a complete approach, that provides a provably optimal solution, while Reche-López et al. compare metaheuristics, that may provide sub-optimal solutions.

Other approaches [Mitchell 1995; Mitchell et al. 1995] make use of a spread-sheet model to support decisions in the coppice harvesting, storage and transport and to model the costs related to the growing short rotation coppices in UK (coppicing is a method of woodland management which takes advantage of the fact that some trees reshoot from the stump or roots if cut down). These approaches converged in [Mitchell 2000] in a comprehensive decision support system based on spread-sheet model for the bio-energy assessment.

An approach making use of a sophisticated MILP model is described in [Freppaz et al. 2003]. Similarly to our approach a Geographic Information System integrated with an Integer Linear Programming model is used. Differently from our approach, the one presented in [Freppaz et al. 2003] relies on an objective function that estimates the economic costs-benefit balance related to the power plant; the benefit derives from the sale of the produced energy, while the costs include the cost of plant installation/maintainance, the transportation cost, the biomass harvesting cost, and the energy distribution cost. Clearly, energy efficiency is not considered while it is an essential aspect in sustainable biomass power plants. Related to the latter, also [Nagel 2000b] makes use of a Mixed Integer Linear Programming model for the definition of an economic energy supply structure based on biomass. The model has been tested in the state of Brandeburg, Germany in [Nagel 2000a]. None of these works consider the (non-linear) function that relates the size of the plant with the energy required to build it, while we approximate it with a piecewise linear function.

Simulation and optimization are compared by De Mol et al. [1997] on the biomass logistic-related problems. The aim is to define the location of the biomass plant along with biomass pre-treatment sites. The optimization model is divided into three components each associated to a type of biomass that are then combined in a knapsack model. The objective function is again the minimization of costs of biomass flow (variable costs) and those related to pre-treatment (fixed costs). Again, energy efficiency is not considered, nor the non-linear relation defining the energy required for building the plant is taken into account.

As explained earlier in this article, it may be the case that the revenue is positive even if the system is not sustainable, and it actually consumes energy instead of producing it; for this reason, we adopted a sustainability viewpoint, that optimizes the net produced energy. We agree that economic factors should not be overlooked, and we explicitly considered the budget of the forest owners.

Another important contribution of this paper with respect to related literature concerns the wider aim of the overall decision support system. It is the first time, to our knowledge, that an effort is done to collect in a unique decision support system all aspects of the strategic environmental assessment along with the corresponding optimization problems. Among these problems biomass location is an important cornerstone.

The formulation of our problem is related to the Facility Location Problem, for which there exists a wide literature on the basic models and algorithms [Kuehn and Hamburger 1963; Balinski 1965; Khumawala 1972; Erlenkotter 1978; Geoffrion and McBride 1978], as well as surveys [Aikens 1985; Brandeau and Chiu 1989; ReVelle and Laporte 1996; Owen and Daskin 1998; Klose and Drexl 2005] and books [Daskin 1995; Sule 2001; Drezner and Hamacher 2002; Farahani and Hekmatfar 2009].

One of the differences in our model with respect to the classical facility location problem stands in the fact that not all clients must be served. Charikar et al. [2001] study various extensions of the facility location in which a small number of clients can be denied service, in order to obtain a reduction of the total cost. In particular, when there is a small number of *outliers*, the cost reduction can be significant. The authors propose various extensions, that can be grouped into two main categories. The *robust facility location* has a fixed parameter p that represents the number of clients that must be serviced; the classical facility location problem can be obtained by setting p equal to the number n of clients. The *facility location with penalties* associates each client j with a penalty p_j: for each client that does not receive the service, the objective function gets the corresponding penalty. Again, the classical facility location problem can be obtained by setting all penalties to ∞. The authors propose polynomial approximation algorithms for these cases.

Brimberg and ReVelle [1998] address the problem as a biobjective problem: the first objective is minimizing the costs, while the second is minimizing the unsatisfied demand. They find the efficient frontier with the weighting method, i.e., they optimize a weighted sum of the two objectives, and then vary the weights to find all the frontier.

In our formulation, if a forest node j does not provide biomass to any plant, the objective function implicitly incurs in a penalty corresponding to its production capabilities $prod_j \cdot E^{wood}$, so our problem could be cast as a facility location with penalties (if the opening cost of each plant was independent of the plant size and there were no upper/lower limits on the plant size).

Holmberg and Lin [1997] consider a variant of the facility location problem in which the cost of a facility depends on the size of the plant through a staircase function; they also propose heuristics based on Lagrangean relaxation. Wollenweber [2008] proposes a number of further extensions to such model and proposes a heuristic approach. Instead of the staircase, we used a continuous piecewise linear approximation of the energetic cost of opening a biomass plant; moreover, our model does not require all clients to be served.

7. CONCLUSIONS

Environmental planning is a delicate area where decision support systems can be important tools in order to allocate resources, e.g. economical incentives, giving a real contribution to the intended strategic objectives and avoiding to adopt policies which, apparently promising, do not tend in practice to the expected goals. As a part of a bigger project oriented to sustainability, we devised, implemented, and tested an optimization tool which addresses the biomass power plant placement problem, in a collaboration between computer science engineers and environmental experts.

Our aim was to produce a constraint model maximizing the environmental sustainability of the power plant, but without forgetting economic factors that could doom the project to failure. We optimized the net energy produced by the whole system, which includes, beside the plant, the collection and transport of biomass to the plant.

In future work, we plan to collect further feedback from operators in the area, we intend to extend and refine the model, customizing it for the various territorial peculiarities. We plan to capture the various points of view (e.g. normative) that environmental agencies face.

Finally, in this work we focussed on just one type of fuel for biomass-powered power plants, namely wood residues coming from forests. Biomass can also come from crops, garbage, or even from manure. It is worth investigating if biomass plants powered with other types of fuel can be optimized with the tools of computational sustainability.

An important extension will be considering further economic issues. For example, in the current work we assumed that each forest node has a different owner, while it can be the case that a single owner has availability of more than one forest. This could have important effects, since an owner could have an advantage in providing biomass to a plant from an unprofitable source, in order to ensure the plant being built, so that other forest nodes in her availability could provide biomass with high profits for her. Indeed, such situations could further increase the issue of sustainability, as unprofitable sources could be far away from the plant, and the transportation of the biomass could have very high energy requirements. We plan to study the issue in future research, by enclosing in our model the information about ownership of the forests.

ACKNOWLEDGMENTS

We are very grateful to the reviewers for their valuable comments on the paper. We are indebted to Alberto Caprara for his suggestions on the proof of NP-hardness.

REFERENCES

AIKENS, C. H. 1985. Facility location models for distribution planning. *European Journal of Operational Research 22,* 3, 263 – 279.

BALINSKI, M. L. 1965. Integer Programming: Methods, Uses, Computations. *Management Science 12,* 3, 253–313.

BEALE, E. AND TOMLIN, J. 1970. Special facilities in a general mathematical programming system for nonconvex problems using ordered sets of variables. In *Proceedings of the 5th International Conference on Operations Research*, J. Lawrence, Ed. Tavistock Publications, 447–454.

BRANDEAU, M. L. AND CHIU, S. S. 1989. An overview of representative problems in location research. *Management Science 35,* 6, 645–674.

BRIMBERG, J. AND REVELLE, C. 1998. A bi-objective plant location problem: cost vs. demand served. *Location Science 6*, 121–135.

BRUGLIERI, M. AND LIBERTI, L. 2008. Optimal running and planning of a biomass-based energy production process. *Energy Policy 36,* 7 (July), 2430–2438.

CHARIKAR, M., KHULLER, S., MOUNT, D. M., AND NARASIMHAN, G. 2001. Algorithms for facility location problems with outliers. In *SODA '01: Proceedings of the twelfth annual ACM-SIAM symposium on Discrete algorithms*, S. R. Kosaraju, Ed. Society for Industrial and Applied Mathematics, Philadelphia, PA, USA, 642–651.

CIP6 1992. Delibera 6 del Comitato Interministeriale Prezzi, 29 aprile 1992 (deliberation 6 of the interministry committee for prices, 29^{th} of april 1992).

DASKIN, M. 1995. *Network and discrete location - models, algorithms and applications*. Wiley, New York.

DE MOL, R., JOGEMS, M., VAN BEEK, P., AND GIGLER, J. 1997. Simulation and optimization of the logistic of biomass fuel collection. *Journal of Agricoltural Science 45*, 219–228.

DREZNER, Z. AND HAMACHER, H. W., Eds. 2002. *Facility location: applications and theory*. Springer, Berlin.

ERLENKOTTER, D. 1978. A Dual-Based Procedure for Uncapacitated Facility Location. *Operations Research 26,* 6 (November-December), 992–1009.

EUROPEAN COMMISSION. 2006. Integrated pollution prevention and control reference document on economics and cross-media effects. Available at http://eippcb.jrc.es/reference/ecm.html.

FARAHANI, R. Z. AND HEKMATFAR, M., Eds. 2009. *Facility Location: Concepts, Models, Algorithms and Case Studies*. Springer, Berlin.

FREPPAZ, D., MINCIARDI, R., ROBBA, M., ROVATTI, M., SACILE, R., AND TARAMASSO, A. 2003. Optimizing forest biomass exploitation for energy supply at regional level. *Biomass and Bioenergy 26*, 15–24.

GAVANELLI, M., RIGUZZI, F., MILANO, M., AND CAGNOLI, P. 2010. Logic based decision support for strategic environmental assessment. *Theory and Practice of Logic Programming 10,* 4-6, 643–658.

GEOFFRION, A. AND MCBRIDE, R. 1978. Lagrangean relaxation applied to capacitated facility location problems. *AIIE Transactions 10,* 1 (March), 40–47.

HOLMBERG, K. AND LING, J. 1997. A Lagrangean heuristic for the facility location problem with staircase costs. *European Journal of Operational Research 97*, 63–74.

KHUMAWALA, B. M. 1972. An Efficient Branch and Bound Algorithm for the Warehouse Location Problem. *Management Science 18,* 12, B–718–731.

KLOSE, A. AND DREXL, A. 2005. Facility location models for distribution system design. *European Journal of Operational Research 162,* 1, 4–29.

KUEHN, A. A. AND HAMBURGER, M. J. 1963. A Heuristic Program for Locating Warehouses. *Management Science 9,* 4, 643–666.

MITCHELL, C. 1995. New cultural treatments and yield optimisation. *Biomass and Bioenergy 9*, 11–34.

MITCHELL, C. 2000. Development of decision support system for bioenergy applications. *Biomass and Bioenergy 18*, 265–278.

MITCHELL, C., BRIDGWATER, A., STEVENS, D., TOFT, A., AND WATTERS, M. 1995. Technoeconomic assessment of biomass to energy. *Biomass and Bioenergy 9*, 205–226.

NAGEL, J. 2000a. Biomass in energy supply, especially in the state of brandeburg, germany. *Ecological Engineering 16*, 103–110.

NAGEL, J. 2000b. Determination of an economic energy supply structure based on biomass using a mixed-integer linear optimisation model. *Ecological Engineering 16*, 91–102.

OWEN, S. AND DASKIN, M. 1998. Strategic facility location: a review. *European Journal of Operational Research 111,* 3, 423–447.

RECHE-LÓPEZ, P., RUIZ-REYES, N., GALÁN, S. G., AND JURADO, F. 2009. Comparison of metaheuristic techniques to determine optimal placement of biomass power plants. *Energy Conversion and Management 50,* 8, 2020 – 2028.

REVELLE, C. S. AND LAPORTE, G. 1996. The plant location problem: New models and research prospects. *Operations Research 44,* 6, 864–874.

SORENSEN, J. C. AND MOSS, M. L. 1973. Procedures and programs to assist in the impact statement process. Tech. rep., Univ. of California, Berkely.

SULE, D. R. 2001. *Logistics of facility location and allocation*. CRC Press.

THOMAS, I. 2008. *The Pros and Cons of Biomass Power*. Rosen publishing, New York.

VOIVONTAS, D., ASSIMACOPOULOS, D., AND KOUKIOS, E. 2001. Assessment of biomass potential for power production: a GIS based method. *Biomass and Bioenergy 43*, 101–112.

WOLLENWEBER, J. 2008. A multi-stage facility location problem with staircase costs and splitting of commodities: model, heuristic approach and application. *OR Spectrum 30,* 4 (Oct.), 655–673.

Received R; revised e; accepted c
eived May 2010; revised August 2010; accepted August 2010