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Multiple criteria decision-making for bio-energy projects assisted by GIS: Current applications and perspectives

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Abstract: Models related to the different stages of bio-electricity production form an integrated model for the evaluation of bio-electricity projects. A variable number of agents is involved in this vertically operating activity. The integrated model can be defined as a Spatial Decision Support System (SDSS) when assisted by a G.I.S. A spatial database containing expert knowledge and environmental models interact with an economic model. This latter is built based on the hypotheses that farmers supply biomass to a competitive market and industry breaks even. As bio-energy chains are currently not viable, the government subsidises this activity in the form of allocated tax exemptions. These subsidies are rendered justifiable to the taxpayers as necessary expenses incurred to reduce the negative effects of fossil fuel energy consumption to the environment.

In order to assist real life complex decision problems, a multicriteria module enables selection among alternative solutions with respect to different criteria. A case study involving bio-electricity project decision-making for the plain of Thessally, Greece, illustrates this methodology. Plant capacity, siting and technology selection are determined simultaneously by the model. The cultivation of cynara and miscanthus was assessed on arid and irrigated land. Land resource is a constraining factor to the system, its availability being subject to increasing opportunity costs. Compromise solutions based on economic, environmental and social criteria are provided by the SDSS with costs that varied between 0.06 and 0.13 €/kWh at biomass marginal costs from 30 to 65 €/t.

A discussion follows on the contribution of such a tool to the development of bio-energy. This requires adaption of the multiple criteria module to the needs of interactive decision-making, and the development of a tool fully operational in a GIS-software environment. Ideally, this tool should be available to the bio-energy community through the use of Internet resources containing full objective information so as to feed public debate on this issue. In this way, pre-feasibility studies of biomass projects to be undertaken in the medium term in Europe could be adequately supported on a regional basis. By fully exploiting G.I.S. technological capacities, public decisions makers will be able to evaluate and appropriately adjust funding and regulation policies.

Keywords: Energy crops, Bio-electricity, Multi-criteria analysis, GIS, Greece.

1. Introduction

The evaluation of bio-electricity projects requires site-specific studies since, unlike conventional systems, bio-electricity plants are supplied with the biomass resources produced by farms located in their vicinity. G.I.S. have been applied to map biomass potential in specific regions for the studies of forestry, industrial, agricultural or livestock residues and have also been used extensively since the 80's in many bio-energy studies, such as the spatial model assessment potential of short rotation woody biomass in Hawaii to supply fuel to conversion facilities (Liu, 1992). In the latter, a system model for estimating biomass production, harvesting and transport costs was developed and applied to a Hawaiian island, while a G.I.S. was interfaced with the bio-mass system model to access a database and present results in a map form. More ambitious works have attempted to assist bio-energy policy at the national level by providing policy makers with quantitative information, not only of an economic but also of an environmental nature,

on potential biomass supplies from energy crops in the U.K. (Cole *et al.*, 1996) and the U.S. (Graham, 1997; 2000) While G.I.S. models can capture geographic variation that affects biomass cost and supply, they are often limited to deterministic analyses in spatial search. In the search for suitable sites for the establishment of the bio-electricity plant, numerical and qualitative criteria are applied to selected siting factors, and the focus area is screened through digital map overlay procedures. However, these procedures can do no more than identify areas that simultaneously satisfy all the specified criteria; in other words, they provide the feasible set of alternatives. The development of bio-electricity systems substituting fossil fuel-driven electricity generators is related to the search for a reasonable balance between environmental and economic objectives in the energy system. Additional techniques are then required to inform the user about which site(s) offer the most promising characteristics for development with respect to different criteria. For this reason, the integration of multi-criteria evaluation methods with G.I.S assisted models was proposed (Carver, 1991).

This paper presents an interactive multi-criteria analysis tool based on the *reference point* method that exploits a spatial decision support system especially developed for the evaluation of bio-electricity projects. Last but not least, it undertakes to develop the interface between standard modelling software and G.I.S. specialised software. This interface permits the spatial visualisation and exploration of alternatives available to the decision-maker by the multi-criteria analysis algorithm. This methodology is presented in the first part of this paper starting by the analysis of the structure of the integrated model. Individual models involved are briefly presented in Appendix I. In section 2.2, the micro-economic nature of the model is justified and the multi-criteria analysis methodology adopted is presented in section 2.3. The above methodology will be illustrated by the presentation of a case study implemented by means of the multiple criteria GIS-assisted decision-making tool in Farsala plain, Greece. The case study is detailed in section 3, with an analytical description of the supply curve generating procedure and the interactive multi-criteria decision making process. Next, we proceed to a description of the integrated model-GIS interface. Perspectives for the exploitation of Internet resources to enhance the decision making process are followed by some concluding remarks.

2. Integrated Bio-Electricity Decision-making (BI-EL.D.) tool

2.1. Modelling structure

Several features of problems inherent to bio-electricity industry render difficult the development of decision-making tools. The modelling of such an industry takes into account a variety of factors such as biomass production, harvesting and transportation, conversion technologies and environmental impacts at all stages of the activity. Since the integration of knowledge obtained in various fields is necessary, several tasks need to be carried out: a) the development of a GIS platform and the computer-based information system to accommodate agro-economic and pedo-climatic data and b) development of the models along the biomass energy chain: energy crop production, harvesting, storage and transportation, biomass supply, biomass energy conversion, environmental and multiple criteria models. Thus, decision-making in the bio-energy field requires analysis of a considerable amount of data and complex relations, as well as the synergy of standard modelling and GIS specialised software. The analysis should be carried out using mathematical modelling that couples all sub-models in order to provide the decision-maker with an aggregate description of the problem and to support rational decision-making. Tools developed for such purposes are referred to as Spatial Decision Support Systems (SDSS). The final decision for the bio-energy development is usually based on a balance of interests of various social groups. A DSS is a valuable tool used to evaluate which decision would be the best one in order to achieve a given set of goals. Thus, goals such as the economic development of depressed areas, environmental objectives, and technological integration and improvement can be examined through a multiple-criteria model analysis. As Lotov (1998) suggests, the above features of issues related to environmental problems should be treated by DSS on the basis of the following methodological principles:

- calculation of aggregated economic and environmental performance indicators using mathematical models to inform policy-makers and all stakeholders on all feasible alternatives.
- generation of the non-dominated set of alternatives.
- display of all trade-offs among the indicators

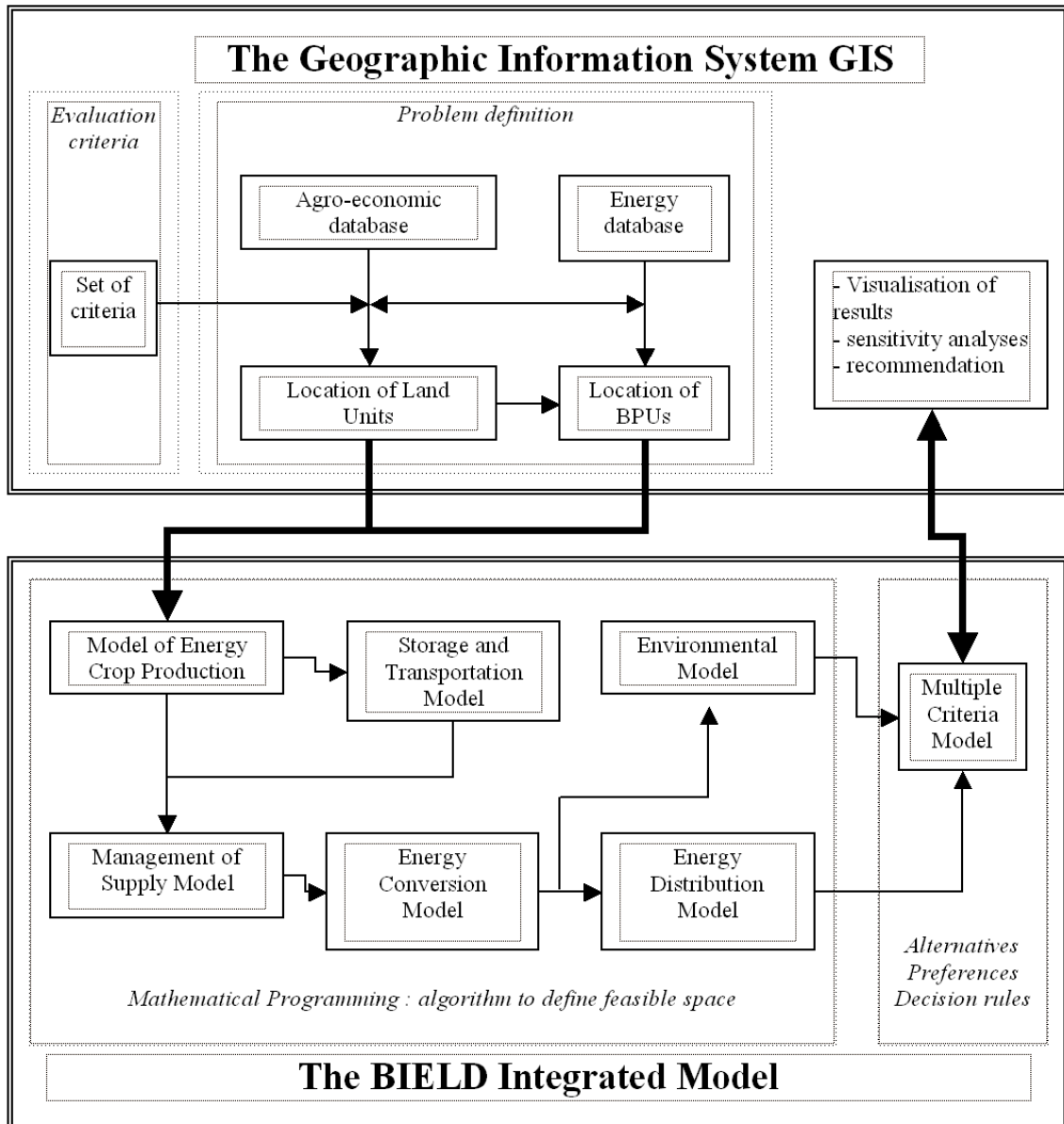


Figure 1. Schedule of data flow in the MULTISEES model.

Source: modified from Saez et al, 2000.

Brief presentations in Appendix I (analytical presentation of the tool in Varela et al., 2001)

Based on the above principles and taking into account specific features related to bio-energy projects, a tool (software application) was developed to assist decision-making for the establishment of bio-electricity systems in rural regions in Southern Europe. This tool was developed within the context of the ALTENER program (Saez et al, 2000), which is not only based on project profitability but also takes into account an assessment of the impact of alternative bio-electricity schemes concerning the environment, local economy, agriculture, employment and pub-

lic expenditure. Public debate can, thus, be facilitated and decision-makers are in position to decide according to preferences and value judgments expressed.

2.2. Economic rationality at the apex of the system

The supply model of biomass feedstock to the energy conversion plant complemented by the model used to assess production costs constitutes a regional micro-economic model. According to Moxey and White (1994), assuming that land use change is driven primarily by individual farmers' responses to changing market and policy conditions, the economic module should be placed at the apex of such a system in order to estimate supply curves of agricultural biomass for energy purposes.

The regional micro-economic model:

- is capable of considering a wide range of various production activities and constraints and links among activities (i.e. rotations) and contains an input and output data structure that is easily transferable (directly linked to detailed cost analysis models)
- is able to incorporate an appropriate level of spatial precision
- is sufficiently flexible to cope with a wide range of policy instruments
- allows for exploration beyond historically observed activity levels
- is replicable (using available standard statistical data and accepted theoretical principles with minimal recourse to local surveys and ad hoc modelling techniques)

Aggregate supply curves for selected energy dedicated crops can be generated at the regional level of exploiting the sophisticated information provided by G.I.S. databases. Information regarding the agricultural production is then introduced to conversion models in the form of supply curves. The potential size of the fuel supply in a region, the size of bio-energy plants for its exploitation, the location of the fuel supply and the cost of biomass delivered to the bio-energy plants can be simultaneously estimated at the "satisficing" optimum for different sets of preferences in the decision space.

This study requires that models be simultaneously linked, and that modelling go a step beyond the simple juxtaposition of diverse economic and environmental elementary models by means of incorporating all relevant models in a functional way. Such an integrated tool is able to evaluate different alternatives for energy crops on the basis of a multiple criteria analysis as demonstrated in the case of biofuel chains in France (Rozakis *et al.*, 2001). It helps decision-makers to adopt policies that encourage the introduction of energy crops into the regional energy system under the current conditions of the Common Agricultural Policy, National Energy Policies and regional institutional arrangements and also allows appropriate measures to be taken to improve the competitiveness of biomass-to-energy projects.

2.3. Multiple criteria methodology

As has been proven elsewhere and also confirmed by the first results in the study, biomass for electricity projects is, in most cases, deficient, especially in the first stage of its deployment. However, many factors, such as environmental concerns, rural development objectives and energy independence policies converge to support biomass implementation. A number of agents are involved in this activity, namely:

- Farmers who should decide whether or not to replace currently cultivated food crops with energy crops
- Cooperatives and entrepreneurs, who may invest in harvesting machinery and other specialised agricultural, transport and storage equipment
- Entrepreneurs, who may invest in the construction of conversion and distribution facilities
- Government and regional authorities, who may support the activity financially on behalf of taxpayers

- politicians and environmental groups, who may be in favour or against this kind of project (in favour with respect to the greenhouse gases and against for pollution reasons such as soil pollution, noise and air pollution in the vicinity of the plant etc.)

Each of the above mentioned agents has a number of interests that may conflict with those of another agent. For instance, public decision-makers who decide upon the allocation of the budget funds may consider budgetary constraints but may also be concerned about public pressure to introduce technologies to reduce the greenhouse gases emissions. Other agents involved may base their decision on purely economic grounds. For instance, farmers expect to sell at prices that result in income greater than that gained from current activities.

Usually, there is no alternative which optimises all criteria simultaneously, so one should look for the best compromise solution according to the decision maker(s') preference structure. For the kind of problems similar to the one tackle in this study, it is important, that the employment of a multi-criteria (MC) analysis be assisted by an interactive tool capable of accommodating the points of view of all interested parties. This would allow for a swift exploration of all possible alternatives and for the enhancement of a dialogue among decision makers.

The following criteria were retained for selection of the bio-electricity plant technology, size and site:

1. cost per unit of electricity produced
2. total amount of subsidies required to make the project viable
3. employment created at the conversion level
4. aggregate agricultural surplus
5. equivalent carbon dioxide emissions saved after substitution with fossil fuels
6. carbon sequestration from substitution of energy with conventional crops

A key concept that will be used extensively throughout the multi-criteria process is the concept of non-domination. A *non-dominated* point, that corresponds to a vector with dimensions equal to the number of criteria, is such that any other point in the decision space that improves the value of one criterion deteriorates the value of at least one other criterion. The solutions corresponding to non-dominated points are called *efficient* or *Pareto optimal* solutions. Any non-dominated point is a candidate for representation of the best compromise solution.

In theory, the Pareto set of optimal solutions is a small subset of feasible solutions, however in practice this subset may include a finite but very large (so for practical reasons infinite) number of solutions, especially when numerous criteria are considered. A procedure that can first generate Pareto efficient solutions has to be implemented in order to examine those that correspond to the DM's preference structure (for methodologies used for continuous and/or discrete variables see also Lotov (1999) in the web site of the Dept. of Math. Methods for Economic Decision Analysis, Russian Academy of Sciences, URL: <http://www.ccas.ru/mmes/mmeda/>).

Usually the number of efficient solutions increases up to several hundreds. Moreover, it is extremely difficult to give a relative importance (weight) to each criterion. Thus, an interactive approach, which allows for exploration of the efficient solutions and for possible trade-offs among criteria, seems more appropriate than any method aggregating a priori the criteria. For this purpose, we implemented an interactive multi-criteria method based on a reference point approach (Wierzbicki, 1982). Basically, this approach projects desirable or aspiration levels expressed by the criteria onto the efficient frontier, resulting in a solution corresponding to a specific bio-electricity scheme.

When the feasible set consists of discrete alternatives, the task is easier and entails comparison of each solution with all the others. A tool that formalises the process is nevertheless required in case of a large number of discrete alternatives.

3. Case-study

3.1 Description of the region and spatial analysis

The region of study is a flat and hilly area, a part of the Thessaly plain, located in central Greece with an average farm size larger than the average for the entire plain. The Spot XS image used focuses on an area about 45.000 ha large extended around Farsala. Additional maps (road infrastructure, electrical network, population concentration, district boundaries) were geo-referenced and digitised based on the satellite image. The geographical layers with the attribute tables were then entered in a G.I.S., SPANS v.7.1, building a relational database.

Through the databases created, information concerning agricultural land was processed to distinguish land classes; land unit with the same soil type, slope, and current land use belonged to the same class. In this case study, the number of classes totalled to 1090. After obtaining this information, expert knowledge was used to estimate yields of all conventional and energy crops examined for each class. As previously mentioned, two perennial herbaceous crops (cynara and miscanthus), which are of specific interest in Southern Europe, were considered. Information on yields of traditional crops is very important as it determines the benefits on which the opportunity cost of land depends. Yields also determine total quantity that a land unit may supply to the plant and consequently affect the particular shape of supply curves.

Table 1. Substitution energy crops options (future) for current agricultural cultivations

Land type	Energy crop potentially cultivated
Non-agricultural use	-
Winter crops	<i>Cynara cardunculus</i>
Summer crops (cotton, corn)	<i>Cynara cardunculus</i> <i>Miscanthuss sinensis</i>
Pastures etc.	-

Elementary units may be farms or land units defined by the G.I.S. These land units would aggregate homogeneous land pieces (pixels) that belong to the same class. Adjacent pixels of the same class form a land unit (LU, in total 12395 land units). Land units may be larger or smaller than real farms. Larger land units are limited by the size of administrative districts (municipalities). Municipalities constitute the smallest administrative units for which agricultural statistics are available by the Greek National Statistics Service (ESYE); in other words, a Land Unit can take as: maximum the size of a municipality when all characteristics related to soil, slopes and current land use are homogeneous within it.

Supply curves determine minimum prices required by farmers at the plant gate to supply the corresponding quantity. They can be used by conversion plants to estimate in a realistic way the cost of biomass feedstock related to quantity. The supply curves generated during this exercise were used by the conversion module of the integrated bio-electricity decision-making model. Note that these curves are specific to a particular site as they include transport costs, and consequently represent the cost at the conversion plant gate, as mentioned in the previous paragraphs. If evaluation is performed for an area considering more than one candidate site, then the process of supply curve generation should be re-iterated as many times as the number of sites in order to select.

3.2. Interactive multiple criteria decision making procedure

The various alternatives, among which one will be decided upon, are generated by the model that links all particular modules of the system (BIELD). The study examines two possible sites in the region of Farsala and four different technologies for bio-electricity generation of variable sizes (constrained by current transmission network capacity and demand for heat in the case of

co-generation). Another constraining factor, which is often ignored, is the visual or noise disturbance that occurs in the vicinity of the plant installation site. Even if the site is isolated, lorries carrying biomass cannot pass through villages at a frequency less than a half hour interval. This can be translated with back-of-the-envelope calculations to plants of 15 MW capacity at a maximum. In this case study, maximum capacities were constrained basically due to heat demand limits of less than 10 MW.

The user must notice that the integrated model should be run as many times as the number of proposed candidate sites for the location of the conversion facility. A thorough observation of the area, the electricity transmission line network, the road network, cities and regional centers, and the potential demand for heat could drastically limit the options available for the location of the conversion plant. For an area of less than 1000 square km, as was the case, where transport distances are limited, only a small number of candidate sites would satisfy all conditions. Candidate sites that respect all the pre-selection conditions are pointed out using GIS query procedures.

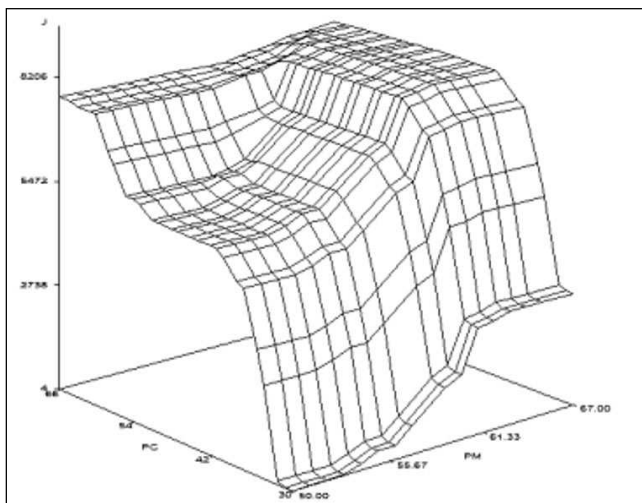


Figure 2. Total biomass feedstock supply (from both cynara and miscanthus in Tcal). In the horizontal axes cynara (PC) and miscanthus prices (PM) are measured.

Model implementation

The integrated model is built as an Excel Visual Basic Application and is named Bio-Electricity Decision-making tool (BIELD). In this application the supply and the conversion models as well as the multi-criteria analysis module are included. When opened, it automatically calls COSTOS, TRAGSATEC, LUC, ENVION and HEAD models which have been developed in separate Excel files.

G.I.S. information and expert knowledge concerning the area are contained in the same Excel file with the TRAGSATEC harvesting, transport and storage model. In total when BIELD application runs, 9 more Excel files are automatically opened (five COSTOS model files –one for each cultivation- and four individual model ones).

Preliminary work

The integrated model is fed by a database file containing relevant information on all Land Units, as well as yields estimated using expert knowledge. This stage is of considerable importance because results depend strongly on yield spatial variability.

Input to BIELDm (GIS attributes).

Id # LU, geo-reference coordinates, Class , Surface , Perimeter, Land type, Slope, Soil type, Administrative district, current crop yields, energy crop yields

Running of the Bio-Electricity Decision-making Application

Based on the above preliminary work and on information given in table 1, the supply curve is calculated as a discrete point surface (for details see Figure 2). For this purpose, a series of intermediate calculations, as described in the "linking models" section, permits estimation of the total costs per ton of energy crops for each land unit. Then, for all possible combinations of prices, the hypothetical farmer who cultivates each land unit selects the most profitable crop (when LU is non-irrigated, he can choose whether to replace or not winter crops by cynara, whereas in the case of irrigated land, he faces the dilemma of replacing the current most profitable crop –cotton or corn- by either cynara or miscanthus). Appropriate cultivation practices and harvesting, transport and storage techniques are provided by cost assessment and transportation models, which are interrogated at this moment. Note that these quantities are not determined independently; they take into account cross-price effects among energy crops.

Output:

Potential biomass supplies for each land unit and related costs and producer's surpluses. Environmental impacts per land unit.

Then the conversion model is run to calculate all criteria values for each price couple and technology configuration (see columns 5-10 in Table 2). The only input from previous level models concerns prices and total quantities of energy crops produced. Additional input to the conversion model: tariffs of electricity, heat and environmental coefficients, specific and annual costs and result values.

The results of the conversion model are presented in the form of discrete alternative configurations of bio-electricity projects. These configurations are identified by technology, capacity level and biomass feedstock quantities related to prices at the plant gate. The number of alternatives is defined by the number of discrete points constituting the supply curve multiplied by the number of technologies and the number of sites (discarding alternatives that do not respect constraints such as those discussed above).

BIELD multi-criteria module is able to discard among the alternatives (which may be hundreds or even a few thousands for a small number of candidate sites –in the case study that considers only two sites, the total number of alternatives approximates one thousand) those dominated by at least another one (on the concept of domination, see section 2.3). Thus, a set of efficient alternatives is selected any one of which is by definition a potential candidate for the final selection as it presents at least one advantage compared to the others. In this case study, a set of 26 alternatives were selected, as shown in Table 6. After the selection of all efficient alternatives by BIELDmc, the criteria and decision spaces are defined. The exploration search and the search for a compromise solution is made in this universe. Columns 2-4 in Table 2 present the characteristics of alternatives, whereas columns 5-10 present the performances of each of the six criteria retained during the decision-making process.

Once non-dominated solutions are known, a matrix that informs the user about conflicts among criteria can be formed. It is the payoff matrix¹ which gives also an idea about the trade-offs² required to improve the solution towards each direction in the decision space. The ideal alternative would be the vector where all criteria attain their optimal value. This cannot be located in the feasible domain so it is also called the Utopian point³. In the antipodes we find the nadir and the anti-ideal points⁴. One can observe that, in this case, there are multiple optima for some criteria, namely cost per unit and labor. Cost minimisation strongly conflicts with other objectives, particularly social (labour, and agricultural surplus) and environmental (CO_{2eq} savings and Carbon sequestration). The four latter objectives are more or less homologous which means

¹ The payoff matrix contains information that can be obtained by the optimisation of each of the objectives over the efficient set and the computation of the value of all other objectives at each of the optimal solutions.

² the trade-off between two criteria means the degree of achievement attained by one criterion that must be sacrificed to gain a unitary increase in the other one

³ *ideal point*: the solution where all the objectives achieve their optimum value. It is also called Utopian point (U-topos denotes that there is no (U in greek) place (topos in greek) within the feasible area where this point could be located)

⁴ *nadir point*: the vector containing the worst elements of the efficient solution set. In this case-study, it coincides with the worst elements from each row of the pay-off matrix

anti-ideal point: the vector containing the worst elements among feasible solutions (dominated and non-dominated).

that when it is desired that one of them attains its optimum, the others also follow suit. One could argue that some of these four homologous objectives should be discarded with. The reason for not doing so is that they concern different agents who may be present in the panel table. Furthermore, it reveals the common interests of these agents.

Table 2. Efficient bio-electricity options for the study-area in Central Greece. Population of non-dominated solutions (BCHP indicates CHP technology located in site B)

technology	prixCyn	prixMisc	capacity	subsidies	cost kWh e	Labor	agrSrplus	CO2eqSav	C_Sequ
identification	€/t	€/t	MW	k€	€/kWh e	#	k€	k tCO2eq	k tCO2
BfluidBdStm	34	61	5	-2339.84	-0.13	8	156.67	43038	1983.0
BfluidBdStm	36	61	5	-2340.84	-0.13	8	157.06	43038	1983.0
BfluidBdGas	38	56	5.01	171	-0.06	7	7.42	32886	1383.0
BfluidBdGas	34	60	5.47	-1728	-0.11	8	100.92	37846	1874.0
BfluidBdGas	36	60	5.47	-1729	-0.11	8	101.3	37846	1874.0
BfluidBdGas	34	61	5.79	-1882	-0.110	8	156.67	40008	1983.0
BfluidBdGas	36	61	5.79	-1883	-0.110	8	157.06	40008	1983.0
BfluidBdGas	38	57	6.37	-219	-0.070	9	16.01	42327	1855.0
BfxdBdGrtStm	38	61	7.09	-2569.27	-0.110	9	163.6	62929	3354.0
BfluidBdStm	38	59	7.29	-1416.25	-0.090	11	63.71	60978	2561.0
BfluidBdGas	38	58	7.32	-512	-0.070	10	38.58	48805	2184.0
BfluidBdStm	36	62	7.88	-3626.69	-0.130	12	237.7	67776	3094.0
BCHP techn	38	61	8.04	-2521	-0.110	7	163.6	63615	3354.0
BfluidBdGas	38	59	8.44	-882	-0.080	11	63.71	56559	2561.0
BfluidBdStm	36	63	8.59	-4024.99	-0.130	13	338.59	73864	3370.0
BfluidBdStm	38	60	9.02	-2133.91	-0.090	13	107.85	75834	3246.0
BfluidBdGas	36	62	9.13	-3071	-0.110	12	237.7	62999	3094.0
AfluidBdGas	32	52	1.09	75	-0.050	2	2.3	7182	303.0
AfluidBdGas	32	53	1.13	64	-0.050	2	2.61	7426	315.0
AfluidBdStm	32	56	4.01	-1340.17	-0.110	7	63.88	34165	1540.0
AfluidBdGas	32	56	4.65	-907	-0.090	7	63.88	31734	1540.0
ACHP techn	32	57	6.4	-1462	-0.120	6	118.66	51666	2857.0
AfluidBdStm	32	57	7.4	-2605.22	-0.110	11	118.66	63290	2857.0
AfluidBdGas	31	57	7.52	-2147	-0.100	10	117.31	51990	2565.0

Based on the pay-off matrix and trade-off bi-dimensional graphs among criteria, the user can set the preference parameters. These consist of inter-criteria parameters (reflecting the relative importance of each criterion such as weights), aspiration points (representing desirable levels for each criterion) and reservation levels (representing minimal requirements for each criterion).

A dialog box containing all the above information is available to the user to enable him to perform all necessary operations related to the multi-criteria analysis by means of which the user can specify aspiration and reservation points, launch the MC module to find the compromise solution closest to his/her goal, and finally visualise this proposed solution.

A special macro procedure shows the map that illustrates the biomass supply associated with any proposed compromise alternative, enabling the user to get a precise idea of the consequences of the selection in terms of biomass feedstock production spatial distribution. The dialog box contains not only preference parameters but also information required to identify the proposed alternative (capacity, biomass feedstock prices).

When the simultaneous optimization of all objectives is sought, in other words, when the utopian point is the target, scrolling bars in the dialog box should be moved to the right side. In this case, the solution, that corresponds to a plant located in site B (near Kiparissos municipality) of Fluidised Bed Gasifier technology using biomass bought at prices at the plant gate of 36 and 61 euro per ton of cynara and miscanthus, respectively, is proposed by the model (efficient alternative corresponding to the target of the ideal point, see Figure 4).

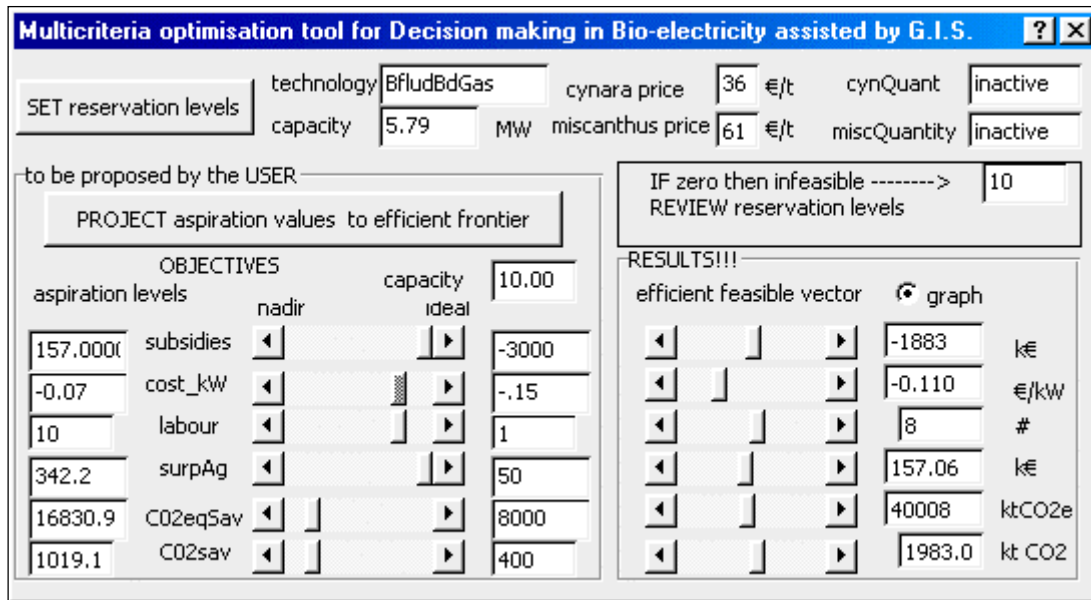


Figure 3. Dialog box of the interactive multi-criteria tool

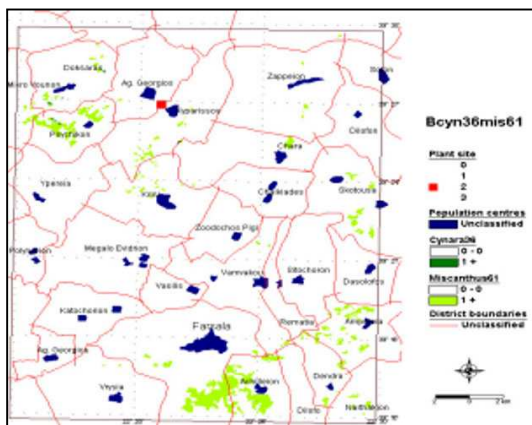


Figure 4. Targeting the efficient alternative closest to the ideal point

This map distinguishes between energy crops, and colors differently Land Units corresponding to different crops. As assumed and explained in the Supply model section, a LU cannot produce more than one energy crop. In the map in Figure 4, only miscanthus is cultivated. If the user is not satisfied with this solution he can try to improve it with regard to a specific aspect. This can be done by selecting the solution previously proposed as the aspiration level, when aiming at the ideal point, and trying to improve it in one or more directions. We observe that site B is selected most of the times when minimization of the subsidy is among the priorities of primary importance and that the technology of Fluidised Bed Gasifier also performs better as a compromise solution as well.

However, when the subsidy target is more moderate, say set at about 1500 k€, then site A is selected along with Fluidised bed gasifier technology of 7.5MW capacity. In both cases, the preferred solution is the use of irrigated land and the cultivation of miscanthus with only a small amount of cynara.

4. Perspectives and further development

4.1 Interface Integrated model-G.I.S.

As explained in the Appendix II, the flow of information between the integrated model and the GIS is in 'batch' mode. The process of calculation is launched once the spatial data and the plant location coordinates are transferred to the model using GIS software. This set of data is loaded by the BIELDm Application in the form of an ASCII file. On the other side of the loop (Fig.5), maps are created by the GIS using BIELD results. Map images cannot be automatically created as the current BIELD version is not directly connected to the GIS. Here, we were obliged to create maps for a large number of solutions pre-designed by the analyst, that essentially comprised all non-dominated alternatives in the decision space. Indeed, in the demo version of BIELD, there are numerous map images corresponding to specific couples of energy crop prices. These maps are stored as .jpeg images easily callable through VB commands by the Application. Simultaneous map creation, as opposed to the "batch" link, can enhance interactivity, save time and improve operational efficiency, if the number of manual 'batch' operations and map reproductions is substantial.

Thus, an interface should be developed between the built-in spreadsheet integrated model and the GIS software to control the operation of the system, and exploit the analytical and illustrative abilities of the GIS software. Various options are available for this purpose, for example:

1. exchange of information by files,
2. use inter-process communication among applications,
3. transcription of the modelling code into the GIS environment.

Different points need be considered to determine the best architecture, for example: does the model need to have easy access to geographic information (GI)? Is there any use for a mode independent of GI? Is there an existing model or is it appropriate to program into GIS- VBA? For GIS, as well as for other applications, there is a standard programming technology. In the new ESRI applications ArcGis (ArcInfo & ArcView 8), customization is performed using the built-in Visual Basic for Applications (VBA) scripting capabilities or a COM-compliant programming language such as Visual Basic, Visual C++, or Delphi. COM is a protocol that links one software module with another. It is possible to build reusable software components that can be interchanged in a distributed system. Within COM, there is the notion of servers and clients. Visual Basic for Applications (VBA) is the new programming environment of ESRI; it uses classical VBA functions and all the specific GIS functions of the ESRI products. Other external development environments that support ActiveX components can also be used. It is very easy to use tools for GUI (Graphic User Interface) creation within the ESRI software.

In order to illustrate the above considerations in the bio-energy case-study, an interface (that can control models built in Excel and/or those written in specialized optimization software (GAMS)) was built in VBA. Alternative ways of interface building between the integrated model and the GIS can be conceived:

- control of the modelling operation and the GIS from within Excel through VBA macro-procedures (to activate specific features of the integrated model)
- control of the interface from the G.I.S. software through VBA
- a more complex option would be to transfer the bio-energy model to the ESRI ArcGis VBA code

This latter option is the most consistent, but at the same time it is the most cumbersome in terms of work time and it may consequently limit the future development of the integrated model because of limited possibilities and flexibility within the G.I.S. software regarding spreadsheet functions. For the above reason, we opted to use both G.I.S. and spreadsheet software and develop interacting linkages between them. This seems to be the most promising path regarding future development of the multicriteria-spatial decision making model (a hybrid of the first two alternatives). In this way, we maintain the benefits of features specific to each software, and limit the computation time of the operation. The proposed configuration allows the user to re-launch the optimization process if necessary and apply different scenarios.

Table 3. Model results in unique tabular form to transfer (export) to the GIS

Land Unit	BfluidBdStm 5MW Alternative in first line table 2		BfluidBdStm 5MW Alternative in second line table 2		...
	BcynaraPrice=34€/t	BmiscanthusPrice=61€/t	BcynaraPrice=36€/t	BmiscanthusPrice=61€/t	
id#	t	t	t	t	
1	0	0	0	0	...
821	0	35,21	0	35,21	...
5233	0	0	0	0	...
5518	28,168	0	28,168	0	...
5799	0	45,27	0	45,27	...
7404	0	45,27	0	45,27	...
8361	0	0	43,3	0	...
8471	0	0	0	0	...
9065	24,144	0	24,144	0	...
...

For this purpose, a macro command that is currently available to automatically lay out map results of the MULTISEES Integrated Model was proposed. This is an example of VBA procedure that is able to:

1. produce a tabular lay out of results in Excel spreadsheet;
2. export results to the G.I.S.;
3. integrate G.I.S. database and Multiple Criteria Model results, and
4. propose a series of map representations corresponding to the final results.

In this example, a unique tabular spreadsheet (Table 3) was exported. It comprised the correspondence of the first column to land unit ID, followed by n couples of columns corresponding to efficient solutions (n denoting the number of efficient or non-dominated solutions). Each couple of columns denotes quantities of *cynara* and *miscanthus* supplied (each line) by land unit. This table is imported to a pre-constructed ArcGis ArcMap file (*.mxd) that comprises the database *join* function and legend layout which presents the results in a cartographic form, as in Fig. 4.

The outcome of the above programming procedure (Fig. 5) is a simultaneous utilization of the two software programs (GIS and spreadsheet) that become available to the user for interaction. Computing time response is immediate and allows the analyst and the decision-maker to analyse alternative solutions and the eventual possibility of re-iterating the algorithm aiming at refined solutions.

An alternative method of data transfer in G.I.S./spreadsheet interaction is the creation of a single results table and a cartographic layout corresponding to every single model calculation. For each software iteration, a 3-column table (land unit ID # and one couple of columns corre-

sponding to model solution for *Cynara* and *Miscanthus* alternative results) is exported from Excel to ArcMap, and one layout at a time is created and stored as back-up file. This way, the speed of the model calculation is optimised in comparison with the unique tabular form transfer. However, the fact that visualization and comparison among different map layouts needs as many iterations as the number of alternatives presents a focus point for further examination (efficient solutions).

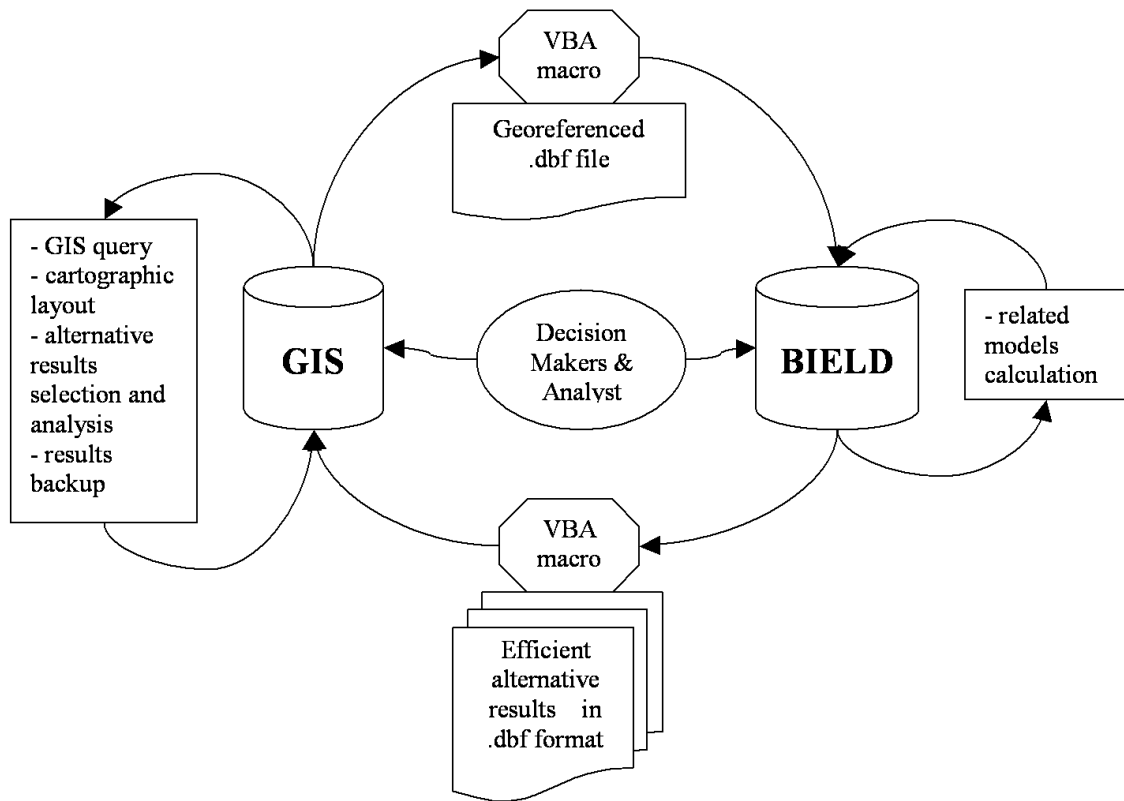


Figure 5. Flowchart of GIS-spreadsheet interface. Automatic operations are represented in octagonal forms while manual operations appear in elliptic shape.

In either way, the results serve as a working tool for agents involved in the use of the model system. The double table/cartographic layout of results is an appropriate tool to be exploited by collaborating agents (section 2.3). Since the training background of stakeholders is different, the integrated layout can be helpful as an assemblance tool to obtain the multi-disciplinary collaboration needed in decision-making projects. A second point of interest in the simultaneous layout of results in a G.I.S. format is the availability of G.I.S. functions to visualize, examine and interpret model results. This analysis and interpretation can be easily understood on the basis of a particular geographical location or spatial specific factor (ex.: soil, altitude, slope, roads, administrative district, land use) not easily accessible by geographically independent data. Thus, the interactive decision-making procedure may result in the final choice or in the choice of a Multiple Criteria Model re-iteration using new information, as well as modified DM preference parameters.

A further possible outcome of a software interaction using the cartographic layout is a change in the input data to be transferred from the G.I.S. to the Excel BIELD model. For example, experts may gain an insight by visualizing the model results in the map and by introducing new information so as to exclude some land units from the analysis for exogenous reasons. A VBA export macro can be conceived to transfer data from ArcMap to Excel and to automatically trigger the calculation procedure, the MC selection process, as well as the generation of cartographic layout with the new set of alternatives available to the DM team. Further development

of the model should provide a systematic back-up of results in a specific folder following the users' will.

4.2 Internet resources and web application development

The SDSS tool presented can be identified in a GSS (Group Support System) in the broad sense defined by Jessup and Valacich (cited in Jankowski *et al.*, 1997) as "computer-based information systems used to support intellectual collaborative (a committed effort on the part of two or more people to devise a new understanding or solution for a decision task) work". However, this collaboration is currently confined to the same location and time. Internet resources could be exploited to enhance it to a decision-making process of increased transparency and the ability of stakeholders (plant location constituency) to consult relevant scientific works would enable to active participation in the decision-making process. To make this possible, special methods need to be implemented using Internet tools. Such techniques (for example, Interactive Decision Maps/Reasonable Goals Method IDM/RGM by Lotov *et al.*, 1997), which imply modifications in the design of the SDSS conceived, were first developed as a stand-alone system. Data access is generally restricted to one user at a time in the GIS. The ArcSDE server allows spatial data to be served to the ArcGIS Desktop (ArcView, ArcEditor, and ArcInfo) and is the key component in managing a multi-user spatial database. ArcSDE is also the GIS gateway that facilitates the management of spatial data in a database management system (Fig. 6).

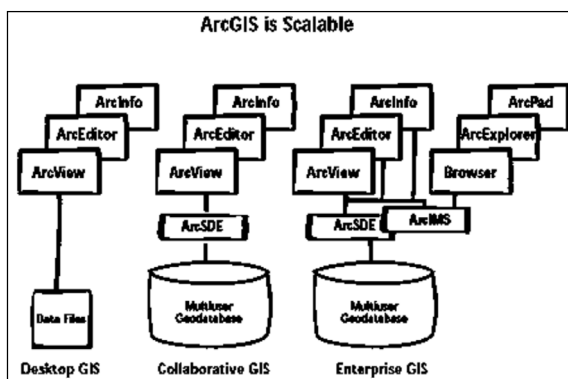


Figure 6. Multi-user database in ArcGIS using ArcSDE

Geographic information could be distributed over the Internet using a Map Server. Various solutions through ArcIMS exist to equip the Web server the GIS capabilities. ArcIms is the map server provided by ESRI. Alternatively, a system developed on the basis of Common Gateway Interface (CGI) scripts could be the solution for the following reasons: it allows the user to work with any OS, information can be stored and updated by the authors, and there is no need for downloading any software. The free open-source MapServer software (<http://mapserver.gis.umn.edu/>) is a well-known server using this CGI solution. The MapServer system now supports MapScript which allows popular scripting languages such as Perl, php, Python, Tk/Tcl, Guile and even Java access to the MapServer C API. Depending on the importance given to modelling internet access in the project specification, the map server architecture may be studied at a very early stage or at the end as an extension to GIS model abilities.

5. Conclusions

The use of spatial D.S.S. proved to be extremely useful in assisting decision-making in bio-electricity project evaluation. An integrated model incorporating GIS and geo-referenced databases into economic and environmental models generated a universe of alternatives regarding bio-electricity production on the plain of Farsala, Greece. Two energy crops competed to provide the bio-electricity plant with raw material (namely miscanthus and cynara), along with four dif-

ferent conversion technologies to electricity. The biomass cost was found to increase with an increase in quantity penalising larger plants in terms of unitary kWh cost as shown in the supply curves. Cost per kWh varied from 0.05 to 0.13 €/t while the subsidies required to ensure operational activity at break even reach a maximum of 4 M€, whereas in a few cases the industry was found to break even without subsidisation. These latter cases concerned fluidized-bed gasifiers of a rather small size (from 1 to 5 MW electric capacity installed).

Supply curve estimations allow calculation of farmers' surpluses, and economic welfare gains or losses. When considering socio-environmental objectives such as job creation and greenhouse gases emission abatement, decision-making is performed on the basis of multi-criteria analysis. Due to the relatively large number of objectives (and interested agents), the resulting efficient alternatives are numerous (24 different bio-electricity configurations in this case). The interactive tool developed to assist the DM process applies a multi-criteria algorithm based on the reference point method so that the solutions proposed are the ones closest to the users' aspiration levels. This tool has been proven to be handy and flexible as it allows the search to be pursued from any point in the decision space in whatever direction. Compromise solutions confirmed the selection of Fluidised Bed Gasifiers when all objectives were given equal importance, but also when budget or environmental considerations prevailed.

When applying the above methodology, the potential to study broader areas with numerous possibilities of plant sites is offered. However, local surveys and biological growth models should be used to improve the quality of economic and agronomic information introduced into the model. The use of biological growth models allows the inclusion of site specific environmental criteria, such as nitrate pollution due to biomass production, and the examination of the different cultivation techniques for energy crops. With regard to the multi-criteria module, improvements could be made to the additional search modes especially in the decision variable space (enabling the user to modify the feasible space during the decision-making process). This latter enhancement requires direct-linkages of the optimization software with that of the GIS in order to get the full benefit of the cartographic abilities of such a system and the information stored in its database. For this purpose, ARC-GIS VBA procedures were built to restore elementary communication within the integrated model. Various alternatives were given in order to make the bio-energy SDSS available on-line for a multi-remote user interactive decision-making process. However, aims and needs should become concrete and further discussion is necessary before the implementation of such a system.

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Appendix I.

The integrated model consists of seven modules, as shown in Figure 1. A brief description of each module is given below. A detailed account of linkages and information flows (input and output flows to and from the models) is presented in the MULTISEES final report to the European Commission⁵:

Module I: Cost analysis of agricultural production (COSTOS) (chapter 3, *ibid*).

This model is used to provide a detailed cost analysis of traditional and energy crops consistent with Net Present Value calculations. It can be used to determine the full cost of biomass production and make financial comparisons among alternative uses of land.

Module II: Harvesting, storage and transportation model (chapter 4, *ibid*).

This model is capable of estimating harvesting, storage and transportation costs for biomass derived from energy crops. It has been structured to analyze biomass harvesting for both herbaceous and woody biomass.

Module III: Biomass supply model (BIELD-supply) (chapter 5, *ibid*).

The supply module is used to estimate supply curves for energy crops. The model assumes that land use is decided upon primarily by individual farmers' responses to changing market and policy conditions.

Module IV: Energy conversion model (BIELD-conversion) (chapter 6, *ibid*).

This model evaluates different technologies for the generation of biomass electricity. Four conversion technologies were examined here (namely fixed bed grate, fluidised bed steam turbine, fluidised bed gas turbine, co-generation heat and power steam turbine). All costs related to the power plant are taken into account and variables can be adjusted to local economic conditions.

⁵ A Multiple criteria decision tool for the integration of energy crops into the southern Europe energy system-MULTISEES I, Report to the European Commission, ALTENER II (ref. CIEMAT/ESEMA/99-C6224/5) published as Varela et al., 2001.

Module V: Energy transport & distribution model (HEAD) (chapter 7, *ibid*).

The energy distribution model calculates the costs of electricity, heat transport and distribution, including all component costs between the plant and consumers.

Module VI: Environmental model (approach based on GORCAM model) (chapter 8, *ibid*).

Among various environmental impacts of energy systems, greenhouse gas (GHG) emissions are identified as major pollutants. The environmental model analyses all possible GHG emissions and is divided into two different parts to assess the GHG balances of

1. land use changes (LUC), and
2. energy systems (ENVION).

The Land Use Change model focuses on the carbon stock change when for example agricultural land is cultivated by short rotation forestry instead of traditional food crops.

The greenhouse gas model is used for the GHG analysis of bio-energy and fossil energy systems based on the total life cycle. All GHG emissions - CO₂, CH₄ and N₂O – resulted from the construction, operation and dismantling of the facilities are included. The fuel chain includes all parts of the electricity or/and heat supply, starting with the extraction of raw materials from nature and ending with the disposal of energy and material to the environment.

Module VII: Multiple criteria model (BIELD-criteria) (chapter 9, *ibid*).

Multiple criteria analysis is used to explore biomass-to-energy project choices. Firstly, decision criteria and objectives need to be determined at the regional level and their consequences identified. For instance, objectives may be the minimisation of energy cost and subsidies, an increase in agricultural income, or the environment sustainability. The model helps to illustrate conflicts and eventual trade-offs among objectives and to find the most promising and compromising alternatives.

Appendix II

The calculation process is launched once the GIS input data and the plant location coordinates are given to the model. This set of data is loaded by the BIELDm Application in the form of an American Standard Code for Information Interchange (ASCII) file. This file constitutes the basis of all calculations and is presented in the sheet "Input" of the file named "Control", as shown in Table 1.

BIELD Application performs all intermediate calculations and results in the generation of supply curves of biomass feedstock at each candidate site, and finally in the set of efficient bio-electricity alternatives for the study area. This process is launched through the Application menu (Bio-Electricity Decision-making command), as shown in Figure 3.

When clicking on the Application menu, a sequence of steps is proposed in the BIELD generic file (a sequence adapted to the case study is embedded in the BIELDemo version). The user should follow the menu commands and execute them one after the other as described below (Demo menu commands to illustrate the sequence of BIELD operations);

- phase 1: drill info (for site A) from linked GIS, economic and environmental models
 - gets models results for site A
 - time lapse: instantaneous
- phase 2: generate supply curve and calculate criteria values
 - generates supply curves for site A and runs conversion model
 - time lapse: about 160-200 sec
 - *put the right values in input boxes (specific data concerning thermal energy)

REPEAT PROCESS for site B.

- phase 1: drill info from linked models
gets model results for site A
time lapse: instantaneous
- phase 2: generate supply curve and calculate criteria values
generates supply curves for site A and runs conversion model
time lapse: about 160-200 sec
*put the right values in input boxes
- phase 3: select Efficient Set, generate Pay-off Matrix and Preference Parameters
prepares necessary tables for MC interactive procedure

A dialog box embedded in the Application facilitates the interactive MC analysis process and responds instantaneously to the aspiration levels set by the user.

The dialog box is called from the menu command "decision-making phase: call interactive MC assistant". This is the moment when the DM involved starts actively participating in the process. At each attempt to attain the aspiration levels set by the user, the model proposes the closest feasible alternative and the user can visualise it through a corresponding map, which shows the spatial distribution of biomass production (see Figure 5 on page 36 of this report).

Maps are created using BIELD results and GIS and they are pre-designed by the analyst. Indeed, in the demo version of BIELD, there are more than 20 map images corresponding to specific couples of energy crop prices. Map images cannot be created automatically, as BIELD is not directly connected to the GIS.

They are created based on the supply curve generated by BIELD for each site (at the maximum, the number of maps required cannot exceed the number of energy crop price combinations times the number of candidate sites). In the Demo case, all maps corresponding to the efficient alternatives are created. Their generation is part of the preparatory work that supports the decision making phase run by the BIELDmc module through the interactive MC dialog box. Thus, before this process starts, all maps that may be needed are created by transferring the BIELD results to ACCES and then to the GIS software that creates the maps. These maps are stored as .jpeg images that are easily callable through VB commands by the Application.

Results give a clear idea about the most suitable location for the agricultural production of energy crops and helps the user to compare alternatives by appreciating supplementary criteria such as the distribution of producer surplus. The process can be repeated iteratively as many times as users consider productive.