

Multi-Criteria Optimal Planning for Energy Policies in CLP

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Abstract

In the policy making process a number of disparate and diverse issues such as economic development, environmental aspects, as well as the social acceptance of the policy, need to be considered. A single person might not have all the required expertises, and decision support systems featuring optimization components can help to assess policies.

Leveraging on previous work on Strategic Environmental Assessment, we developed a fully-fledged system that is able to provide optimal plans with respect to a given objective, to perform multi-objective optimization and provide sets of Pareto optimal plans, and to visually compare them. Each plan is environmentally assessed and its footprint is evaluated. The heart of the system is an application developed in a popular Constraint Logic Programming system on the Reals sort. It has been equipped with a web service module that can be queried through standard interfaces, and an intuitive graphic user interface.

KEYWORDS: CLP applications, Strategic Environmental Assessment, Regional Energy Planning

1 Introduction

Policy making, in the current connected world, has to consider such a number of issues that a single person cannot possibly consider without introducing vast approximations. For example European regions should provide Regional Energy Plans to define strategic objectives and political actions for the energy sector, considering:

- the current energy balance in the region (produced/consumed energy, imported/exported, electrical/thermal, etc.)
- forecasts for the following years, about energy request or production costs;
- existing and new directives, e.g. the EU 20-20-20 initiative that poses three challenging targets for 2020: 20% improvement of energy efficiency, 20% of the energy produced from renewable sources, and 20% reduction of greenhouse gas emissions.

The policy contains strategic objectives on the energy share and energy efficiency, measures and activities to cope with the increased energy needs, new regulations, etc. Regional plans in particular are typically very high-level: they include activities such as building new power plants for some total output power, the share of each fuel type (nuclear, fossil fuels, biomasses, etc.) and the type of produced energy (electric or thermal); but they lack information about, for example, the actual placement of the plants in the region, since more detailed plans will be done at lower scale, like the province or municipality levels. By EU directives, regional policies on the energy sector should also include an environmental assessment of the plan. Being the plan so high-level, usually the assessment is done only in a qualitative way.

In a previous work (Gavanelli et al. 2010), we proposed and compared two alternative logic programming formulations for the strategic environmental assessment of regional plans; one was based on probabilistic logic programming, the other on **CLP!** (CLP!) (Jaffar and Maher 1994). We also developed four fuzzy-logic formulations of the assessment problem (Gavanelli et al. 2011). All these programs consider a regional plan, given in input, and provide its environmental assessment. In a following work (Gavanelli et al. 2013), the **CLP!** program was extended to generate plans together with their assessment, and it was used during the definition of the Regional Energy Plan 2011-2013 of the Emilia-Romagna region (Pilolli et al. 2011).

In this work, we show how the first prototype of the planner was extended to a fully-fledged application. In particular, the current version of the software supports:

- plans that consider decommissioning obsolete power plants;
- computation of emissions of the power plants for various types of pollutants, in a quantitative way;
- quantitative assessment of the effect of the plan on human health, global warming, and acidification potential;
- multi-criteria optimization considering a variety of objective functions based on qualitative and quantitative information;
- computation of the Pareto front, for two or more objective functions;
- a web service, providing access through a **GUI!** (GUI!) and APIs.

This work is one of the components of the EU ePolicy project¹. The final application will include also an opinion mining component, to assess the acceptance of the policies from the public considering information coming from blogs and social networks; a social simulator component, that will simulate how the population will react to the policies adopted by the Region; a mechanism design component, that will include information

¹ <http://www.epolicy-project.eu>

from game theory to provide the best allocation schemes of regional subsidies to the stakeholders; and an integrated visualization component.

The rest of the paper is organized as follows. We first introduce the planning and environmental assessment as they are currently done by experts in the Emilia-Romagna region of Italy, and recap the basic CLP! program of the first prototype (Section 2). In Section 3, we extend it with new features. We show the design and features of the web service and GUI! in Section 4. Finally, we conclude in Section 5.

2 Problem considered and CLP solution

The strategic environmental assessment, in the Emilia-Romagna region of Italy, is currently performed by considering two matrices, called *coaxial matrices* (Cagnoli 2010). They are a development of the network method (Sorensen and Moss 1973), and they contain qualitative relations.

The first matrix, \mathcal{M} , considers the *activities* that can be undertaken in a plan, and links them with the *environmental pressures*. Pressures can be positive or negative, and they account for the impact on the environment of human activities. Each element m_j^i of the matrix \mathcal{M} can take values $\{high, medium, low, null\}$, and defines a qualitative dependency between the activity i and the negative or positive pressure j .

The second matrix, \mathcal{N} , relates the pressures with the *environmental receptors*, that register the effect of the pressures on the environment. For example, the activity “coal-fueled power plant” generates the pressure “emission of pollutants in the atmosphere”; on its turn, this influences the receptor “air quality” (as well as other receptors, like e.g. “human wellbeing”). Each element n_j^i of the matrix can take the qualitative values: *high*, *medium*, *low* or *null*, and defines the dependency between pressure i and receptor j .

Currently, the matrices relate 115 activities with 29 negative and 19 positive pressures, and 23 receptors. They can be used to assess a variety of regional plans, including Agriculture, Forest, Fishing, Energy, Industrial, Transport, Waste, Water, Telecommunications, Tourism, Urban plans. The environmental assessment is usually done using a spreadsheet and deleting (by hand) those activities that do not belong to the given type of plan; then pressures and receptors that are not influenced by remaining activities are removed accordingly. The “reduced” matrices are evaluated by environmental experts, that state which parts are most important, mainly considering clusters of *High* values.

Clearly, this process is very slow, experts might overlook important combinations of *medium* or *low* values, and, most importantly, it can be done only after the plan has been provided by the policy maker. At this stage, usually only minor modifications can be back-propagated to the plan, and comparing a plan’s effects with alternative plans is not possible without starting another planning phase.

2.1 A CLP solution

To overcome the limitations and improve on current practices, we devised a **DSS!** (DSS!) able to provide optimal plans and environmental assessment (Gavanelli et al. 2013): the planning problem was modelled as a linear program in CLP! on the Reals sort (CLP(\mathcal{R})).

Given a number N_a of activities, we consider a vector $\mathbf{A} = (a_1, \dots, a_{N_a})$ in which we associate to each activity a variable a_i that defines its magnitude. The domain of a_i

depends on the availability of the resource on the given Region; for example some regions are very windy, while others can exploit better biomasses or solar energy.

We distinguish primary from secondary activities: primary activities are directly related to the given type of plan, while secondary ones are those supporting the primary activities by providing the needed infrastructures. E.g. in an energy plan, primary activities are those producing energy (e.g., power plants), and they may require other activities (e.g., power lines, waste stocking, streets, etc.) that have an environmental impact too. Let A^P be the set of indexes of primary activities and A^S that of secondary activities. The dependencies between primary and secondary activities are considered by the constraint:

$$\forall j \in A^S \quad a_j = \sum_{i \in A^P} d_{ij} a_i \quad (1)$$

Each activity a_i has a cost c_i ; given a budget B_{Plan} available for a given plan, we have:

$$\sum_{i=1}^{N_a} a_i c_i \leq B_{Plan} \quad (2)$$

Given an expected outcome out_{Plan} of the plan, we also have:

$$\sum_{i=1}^{N_a} a_i out_i \geq out_{Plan}. \quad (3)$$

E.g. an energy plan outcome can be to increase available energy, so out_{Plan} could be the added availability of electrical power (in kilo-TOE, Tonnes of Oil Equivalent). Other outcomes can be considered, e.g. increasing only renewable energies.

Concerning the impacts of the regional plan, an environmental expert suggested to convert the qualitative values in the matrices into coefficients ranging from 0 to 1; we sum up the contributions of all the activities to estimate the impact on each pressure:

$$\forall j \in \{1, \dots, N_p\} \quad p_j = \sum_{i=1}^{N_a} m_j^i a_i. \quad (4)$$

Similarly, given the pressures $\mathbf{P} = (p_1, \dots, p_{N_p})$, the influence on the environmental receptor r_i is estimated through the matrix \mathcal{N} , relating pressures with receptors:

$$\forall j \in \{1, \dots, N_r\} \quad r_j = \sum_{i=1}^{N_p} n_j^i p_i. \quad (5)$$

Possible objective functions include maximizing/minimizing the produced energy, the cost, or one of the receptors (e.g., “air quality”), or a linear combination of the above.

3 Extended solution

The CLP(\mathcal{R}) program described in Section 2.1 was used in the development of the 2011-13 Regional Energy plan of the Emilia-Romagna region of Italy: the plan objective was to increase the share of renewable energy in the energy mix, and to fulfil the 20-20-20 directive. For the next years experts foresee the decommissioning of carbon-based power plants, with a residual utilisation when renewable energy is unavailable or in peak hours. Region experts asked us to extend the DSS! to consider also the closing of power plants.

Power plants decommissioning implies that some activities have a negative magnitude: e.g., the magnitude, in MW, of oil-based power plants could be reduced w.r.t. the previous years. However, negative activities introduce non-linearities. For example, if building a new plant i has a cost c_i in €/MW, decommissioning it will not give a *profit* of c_i €/MW.

Our implementation is based on the ECLiPS^e CLP language (Apt and Wallace 2007; Schimpf and Shen 2012), using the eplex library (Shen and Schimpf 2005). The eplex library uses very fast solvers using linear programming or mixed-integer linear programming algorithms, allowing the use of linear constraints on variables ranging either on continuous or on integer domains. It is well known that linear programming is polynomially solvable, while (mixed) integer linear programming is NP-hard; thus the efficiency of the solution depends on whether there are integer variables or not. To address the non-linearity, we introduced, for each activity a_i that has negative values in its domain, a real variable Pos_i defined as:

$$Pos_i = \begin{cases} a_i & \text{if } a_i \geq 0 \\ 0 & \text{if } a_i < 0 \end{cases}$$

The cost constraint (2) is now rewritten as:

$$\sum_{i=1}^{N_a} Pos_i c_i \leq B_{Plan}. \quad (6)$$

Similarly, secondary activities should not be decommissioned together with primary ones; so we impose their relationship only with the positive part of primary activities.

Concerning the environmental assessment, we may notice that any new activity has different types of impacts, some related to its initial implementation (e.g., land use for building a coal power plant), and others due to the activity functioning (e.g., air pollution for burning fuel). Equation (4) correctly accounts for both when dealing with “positive” activities, while would be incorrect w.r.t. “negative” activities.

To cope with the activities decommissioning, the co-axial matrices have been extended with new activities (e.g., “*Reduced use of fossil fuelled power plants*”). All the pressures are now computed on positive activities only, and Equation (4) is substituted with

$$\forall j \in \{1, \dots, N_p\} \quad p_j = \sum_{i=1}^{N_a} m_j^i Pos_i. \quad (7)$$

We considered the new activities as a new type of secondary activities: the “*Reduced use of fossil fuelled power plants*” is a secondary activity that becomes positive only when activities like “*Coal-based power plant*”, etc., has a negative value (i.e., in case of decommissions). Hence, we now have two matrices of dependencies between activities: a $N_a \times N_a$ square matrix \mathcal{D}^+ where each element d_{ij}^+ represents the magnitude of activity j per unit of activity i ; and another $N_a \times N_a$ square matrix \mathcal{D}^- where each element d_{ij}^- represents the magnitude of activity j per unit of reduction of activity i . Equation (1) is updated with

$$\forall j \in A^S \quad a_j = \sum_{i \in A^P} K_{ij} \quad K_{ij} = \begin{cases} d_{ij}^+ \cdot a_i & \text{if } a_i \geq 0 \\ d_{ij}^- \cdot (-a_i) & \text{if } a_i < 0 \end{cases} \quad (8)$$

3.1 Computing emissions

A further extension to the model presented in Section 2.1 has been about the evaluation of emissions in quantitative terms. To this end, we rely on the data provided by two databases: INEMAR (Caserini et al. 2002) and ISPRA (ISPRA): both databases provide the various types of pollutants² emitted per fuel unit (in GJ). While ISPRA provides the average emission for each plant type, INEMAR provides fine grained information, in which also the type of boiler and the size of the plant (in MW) are considered.

Let N_B the number of boiler types, and $\mathbf{B} = (b_1, \dots, b_{N_B})$ a vector of constrained variables where b_i is the total output power of plants using boiler type i . Let \mathcal{O} be the matrix that relates power plants and the different kinds of boiler: each element o_j^i of the matrix is set to 1 if the boiler $b_j \in \mathbf{B}$ can be used for the power plant $a_i \in \mathbf{A}$, and zero otherwise. The output power of each plant type is the sum of the power of its boilers:

$$\forall i \in \{1, \dots, N_a\} \quad a_i = \sum_{j \in N_B} o_j^i b_j \quad (9)$$

Let $\mathbf{E} = (e_1, \dots, e_{N_e})$ be the vector of emissions and \mathcal{T} the matrix relating them with the boilers. An element $t_j^i \in \mathcal{T}$ represents the grams of pollutant $e_i \in \mathbf{E}$ emitted when 1GJ of fuel is provided to the boiler $b_j \in \mathbf{B}$. To calculate the emissions, we have to compute the input energy for each boiler type j , provided the output power b_j :

$$\forall i \in \{1, \dots, N_e\} \quad e_i = \sum_{j \in N_B} t_j^i \left(\frac{T^U}{\eta} b_j \right). \quad (10)$$

T^U is the average running time of a power plant per year (necessary to convert energy into power) and η is the average efficiency (output power/input power) of power plants, which is prescribed by law as 39% (Autorità per l'Energia Elettrica e il Gas 2008).

3.2 Indicators

Thanks to the extension presented in Section 3.1 it is possible to evaluate quantitatively the emissions of some gases, metals, etc. Such data can be exploited to consider plans aiming to minimize them; however, it is not clear how to compare the emissions. E.g., a policy maker could know that **NOx!** are toxic for humans, but how does that compare with heavy metal emissions?

The European Commission (2006) published a set of indicators quantifying the effect of various substances on *human toxicity*, *global warming* and *acidification*: e.g., the Annex 1 contains 100 chemicals with their human toxicity factor, defined as the toxicity of the substance compared to that of lead (Pb). By using the weights in the tables, one can provide, e.g., the total human toxicity (in kg of *equivalent emitted Pb*), the global warming effect (kg of *equiv. CO₂*) and the acidification of the plan (kg of *equiv. SO₂*). Moreover, a policy maker may want to optimize on these indicators (by directly minimizing them or any weighted sum).

² Considered types of pollutants include **SOx!** (**SOx!**), **NOx!** (**NOx!**), methane, *CO*, *CO₂*, *N₂O*, ammonia, **HCB!** (**HCB!**), various metals (Arsenic, Cadmium, Chromium, Copper, Mercury, Nickel, lead, Selenium, Zinc), particulate matter (PM10), Dioxins, and some families of compounds, like **PAH!** (**PAH!**), **PCB!** (**PCB!**), and **NMVOC!** (**NMVOC!**).

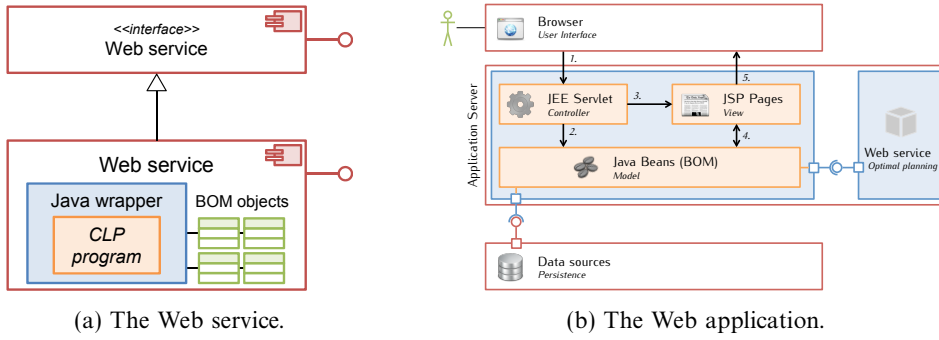


Fig. 1: Software stack to deploy the CLP! program as a Web service and the typical MVC! pattern to exploit it as a Web application.

However, the tables provided by the EC do not always have the same granularity of the information available for emissions. For example, for each plant type we know the emissions of NO_x !, while in the EU report there are the single toxicity values of NO and NO_2 (and they are quite different: respectively, 95 and 300 times that of Pb). Environmental experts suggested to provided as output, for each indicator, the best, worst, and average cases, considering respectively the highest toxicity in the compound class, the lowest and an average. If one of the indicators is in the objective function (e.g., one wants to find the plan with minimum human toxicity), we optimize the worst case.

3.3 Computing the Pareto front

The approach presented in Section 2 allows to optimize w.r.t. a single function. However, in the case of regional planning it is very hard (if not impossible) to devise a unique function that includes all the objectives that are important for the user. Hence, we added a further extension towards multi-objective optimization.

In a multi-objective optimization problem, a solution is *Pareto optimal* if it is not possible to improve the result for one objective function, without worsening at least another objective function. More precisely, in a multi-objective problem with n functions to minimize, a solution μ^* is *Pareto-optimal* if there does not exist another solution μ such that $\mu_j \leq \mu_j^*$ for $1 \leq j \leq n$ and there exists at least one i , $1 \leq i \leq n$ such that $\mu_i < \mu_i^*$. The set of Pareto points is distributed on the so-called Pareto frontier.

We implemented the *normalized normal constraint method* (Messac et al. 2003), an algorithm that works with any type of constraints (linear and nonlinear) and variables (continuous and discrete), and that is able to find an *evenly distributed* set of Pareto solutions. In this way, the policy maker is provided with a set of solutions that are a good representation of the whole space of the Pareto frontier.

4 Graphical User Interface

Usually, policy makers are not IT-experts. To ease the access to the DSS, we deployed the CLP! planner as a stateless Web service and access it by means of a stateful Web application. The CLP! program is embedded inside a Java wrapper (Fig. 1a) that encodes the requests in

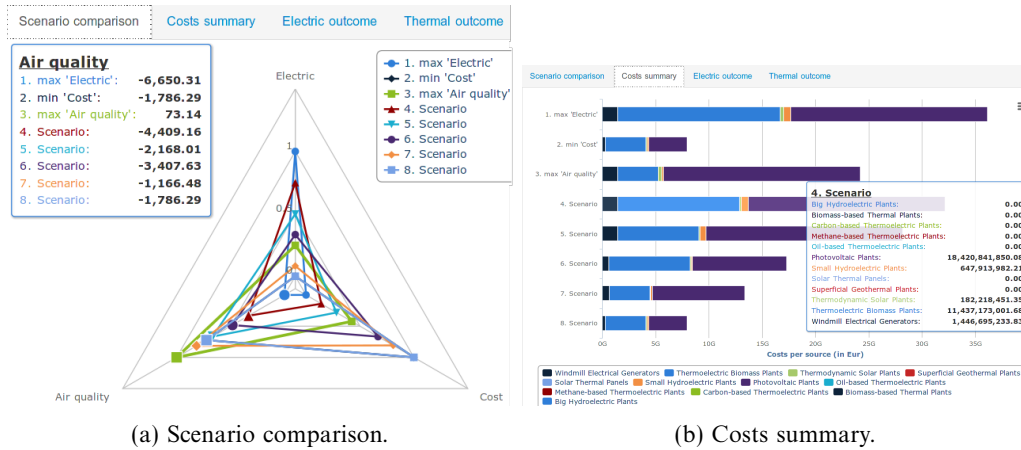


Fig. 2: The views associated with the *General overview* entry for *Scenarios comparison*.

CLP! terms and decodes the results. This component provides a plethora of Java classes that represent the **BOM!** (BOM!) of this domain. Any query addressed to this component and all the returned results are expressed in terms of these objects. We adopted the Apache CXF framework to support the Web Service implementation. The Web application that stands as a GUI for the Web service is a standard Java servlet (Fig. 1b) following the **MVC!** (MVC!) pattern and can be accessed at: <http://globalopt.epolicy-project.eu/Pareto/>.

After a welcome page that introduces the software, there are an input page, and a results page. As input the user can provide minimum and maximum bounds for each energy source, constraints, and objective functions for the Pareto optimization (together with a desired number of Pareto points). Constraints and objectives can include linear combinations of cost, produced power, receptors, emissions, or indicators.

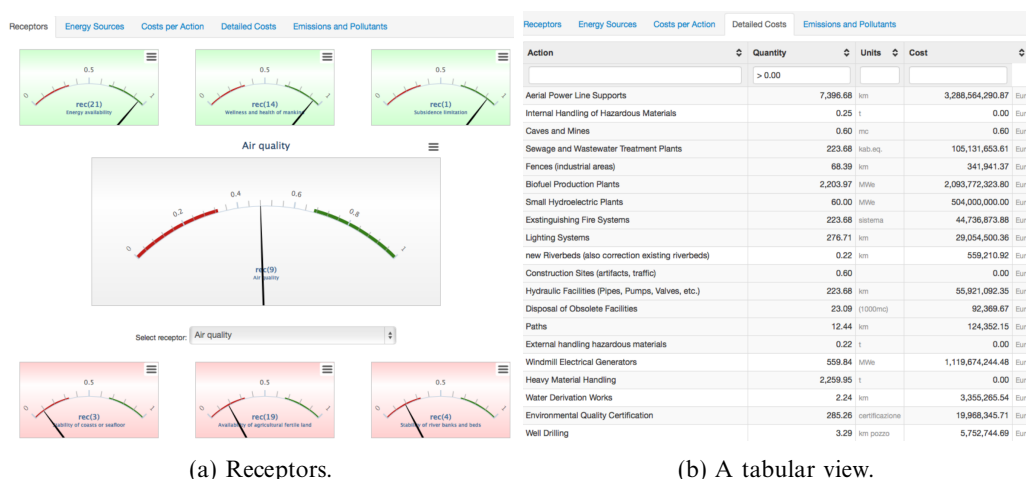
As a result, a set of graphs allow to inspect details on a specific plan (scenario), and/or to compare the computed plans. Scenarios are divided into *boundary scenarios*, that are those that optimize one of the objective functions, and *intermediate scenarios*, that try to balance the various objectives.

Scenarios comparison. Scenarios can be compared through a *spiderweb chart* (Fig. 2a) that has an axis for each objective function. Along each axis, the optimal values are far from the origin, and each scenario is represented by a polygon. Roughly speaking, a bigger polygon implies a better scenario (note that these solutions are Pareto optimal, so one polygon cannot be completely included into another polygon).

Scenarios can also be compared through *stacked bar chart*, showing, for each scenario, the distribution of costs per energy source (Fig. 2b), or the amount of electric/thermal energy per source. Moreover, a further view provides scenarios comparison in terms of pollutants (*Heavy metals*, *Greenhouse gases*, and *Other pollutants*), by means of basic column charts.

Scenarios Details. For each scenario, the following views are available:

- *Receptors.* This composite view uses 7 *VU-meter charts* (Fig. 3a). The top part shows the 3 receptors with the best normalised value, while the bottom one the 3 with the



(a) Receptors.

(b) A tabular view.

Fig. 3: Details views for each scenario.

worst normalised value. The main chart allows the user to select any receptor and appraise its normalised value. This specific view ensures fast access to the best and worst receptors for the specific scenario.

- *Other views.* There are four interactive *tabular* views (Fig. 3b) showing respectively, for the chosen scenario, the amount of produced energy per source, the total cost for each energy source to be spent in primary and secondary activities, the detailed costs for each activity, and the list of emissions.

5 Conclusions and Future Work

We presented a decision support system with optimization based on CLP! for the regional planning, with particular emphasis on the environmental aspects. The program was practically used to produce the energy plan 2011-2013 of the Emilia-Romagna region in Italy (Pilolli et al. 2011), and it is foreseen to use it also for the forthcoming plans. The CLP! program is included into a standard web service, and it has been equipped with an intuitive GUI. The CLP! program will be the heart of the platform of the EU FP7 ePolicy project, that will also include components like a social simulator, an opinion miner, and a mechanism designer, all governed by the described CLP! program. Preliminary work has been done on its integration with the mechanism designer (Milano et al. 2012), and a social simulator (Borghesi et al. 2013).

Future work will be on extending the model at a more detailed level, e.g. taking into account decommissioning fixed costs.

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