ePolicy

Engineering the Policy-making Life Cycle

Design of the Global Regional Model and its instantiation on the Energy plan

Document type:	Deliverable
Dissemination Level:	Public
Editor:	Michela Milano
Document Version:	0.1
Contributing Partners:	UNIBO, UNIFE, ASTER, RER
Contributing WPs:	WP3
Estimated P/M (if applicable):	12
Date of Completion:	15th of October 2012
Date of Delivery to EC	31st of October 2012
Number of pages:	42

ABSTRACT

The aim of this document is to start from the requirements of a decision support system able to support regional planning defined in deliverable 2.1 and to design a model for the global optimizer, developed in task 3.3, that takes into account the regional perspective. Clearly being the project focussed on the Regional Energy plan, we will instantiate the requirements for this plan, but the defined model can be also extended for other plans.

The regional energy plan describes the current situation, the regional Energy Balance, the strategic directions of the region in the production of energy in renewable energy sources and interventions to promote energy efficiency. We consider here only the energy production from renewable energy sources. In this setting, the policy making process should be at the same time consistent with constraints, optimal with respect to given objectives and assessed to avoid negative impacts on the environment, economy and society.

SEVENTH FRAMEWORK PROGRAMME

The project is co-funded by the European Community under the Information and Communication Technologies (ICT) theme of the Seventh Framework Programme (FP7/2007-2013). Grant Agreement n°288147.

Authors of this document:

Michela Milano[1], Attilio Raimondi[2], Marco Gavanelli[3], Fabrizio Riguzzi[3]

[1]: DEIS, University of Bologna
email: michela.milano@unibo.it
[2]: Regione Emilia Romagna
email: ARaimondi@regione.emilia-romagna.it
[3]: ENDIF, University of Ferrara
email: {marco.gavanelli, fabrizio.riguzzi}@unife.it

Contents

1 Introduction

Policy making in the energy sector accounts a crucial aspect of energy production and energy efficiency that heavily affects economic development, sustainability, and social acceptance. Our energy production is heavily relying on burning fossil fuels, that beside being near exhaustion and coming from politically sensitive regions of the word, produce carbon emissions that are responsible of climate change. Against this background, energy policy making is turning attention toward sustainable energy policies and low carbon economy, by possibly eliminating the direct use of fossil fuels, targeting renewable energy sources, promoting energy efficiency and strategically going toward the smart grid.

Regional planning is the process implemented by regions to foster their objectives and put them into actions. There are four steps in the policy making process as depicted in figure 1: policy planning, environmental assessment, implementation and monitoring. In the planning step, strategic objectives are set, budget constraints are defined, geo-physical constraints are considered. In the case of energy planning, an example of strategic objective is to pursue the EU 20-20-20 initiative at regional level, while an example of constraint can be the maximum energy that could be produced by a given source due to geo-physical characteristics of the region.

The assessment phase, that is traditionally performed after the planning step, concerns the evaluation of the impact of the policy plan on the environment, and to a certain extent on economy and society. Planning and environmental assessment are performed now in sequence. This means that in case a plan contains negative effects on the environment, only corrective countermeasures can be applied a posteriori. Instead, in case the planning and the environmental assessment were performed at the same stage, an environmentally assessed plan could be produced instead.

Implementation consists in defining a set of actions to pursue the planning objectives, like incentives, information campaigns, compulsion and so on. The monitoring step is performed ex-post, to check if the implementation strategies achieve the expected objectives settled during the planning phase.

In this deliverable, we take into account only the first two phases of the policy making process: planning and environmental assessment.

For the environmental assessment we have experimented three models: a probabilistic model, a fuzzy model and a linear model. The reason to evaluate more models is that the matrices used by environmental experts are indeed interpretable in different ways and we were looking for the best possible choice. We will underline pros and cons of each of them and come out with the final model used in the project. On top of this model, the planning phase is inserted to come up with a single model for planning and assessment. The model has been evaluated on data for the Emilia Romagna regional energy plan 2011-2013 and compared with the plan produced by regional experts.

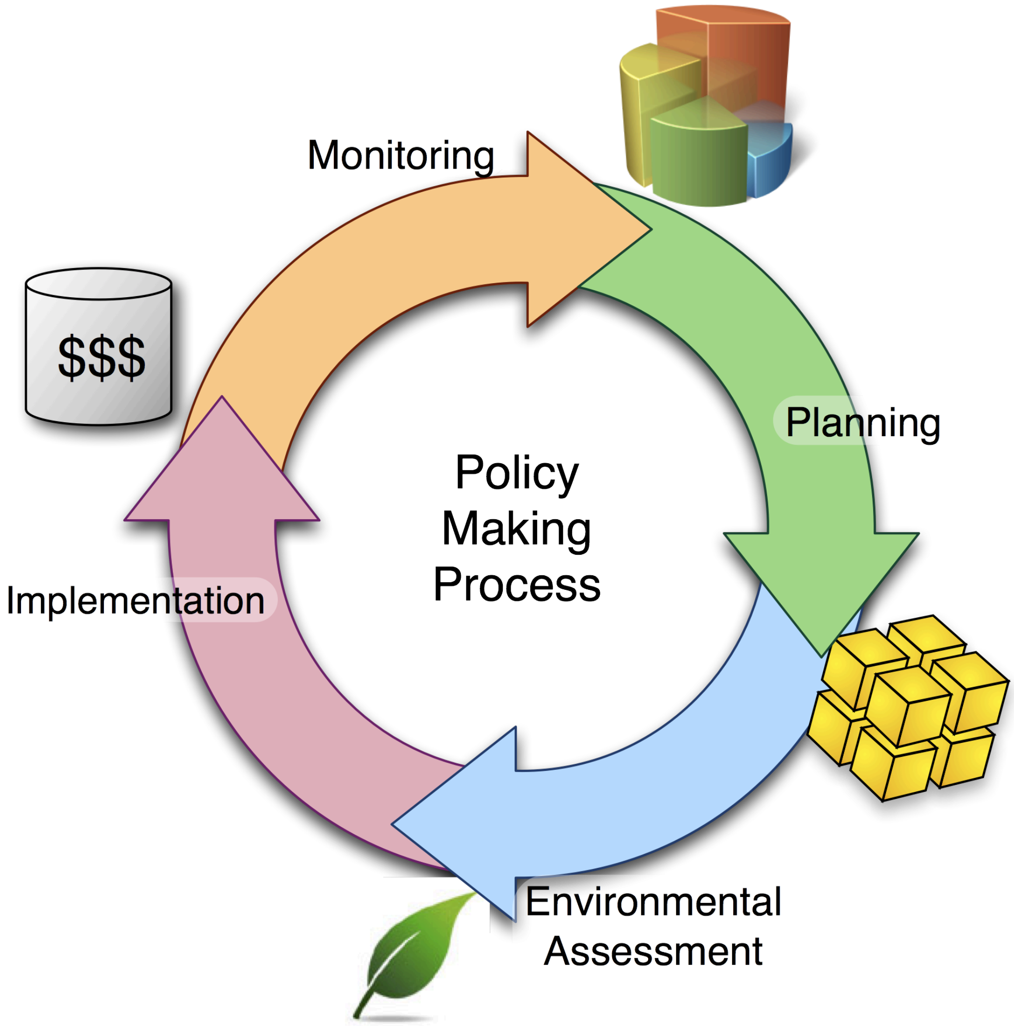

Figure 1: The policy process phases

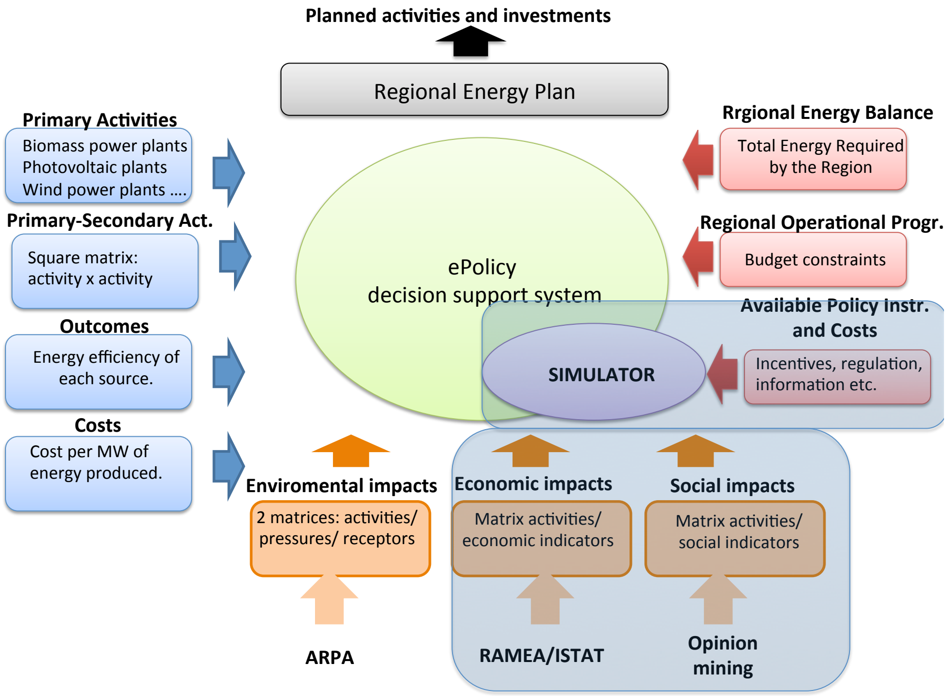

Figure 2: High level overview of Inputs and Outputs of a DSS for ePolicy. The shaded part is not considered in this deliverable

2 Regional Planning and Impact assessment

The Regional Plan is the result of the main policy making activity European regions are involved in. Each region has a budget distributed by the Operational Programme (OP): an OP sets out each region priorities for delivering the funds. On the basis of these funds, the region has to define its priorities: in the field of energy, one example of priority is increasing the use of renewable energy sources.

Starting from the structure of the decision support system described in Deliverable 2.1, we are now devising a model for the global optimizer which is taking into account the regional perspective. Clearly, in the general picture of the overall DSS we do not consider here some aspects related to the integration with the simulator and with the opinion mining part. Therefore, the overall structure we consider here is the one depicted in Figure 2.

In the planning phase, a region should decide which activities to insert in the plan. Activities may be roughly divided into six *types*:

(1) infrastructures and plants;
(2) buildings and land use transformations;
(3) resource extraction;
(4) modifications of hydraulic regime;
(5) industrial transformations;
(6) environmental management.

Also, a magnitude for each activity should be decided describing how much of a given activity is performed.

We therefore have a number of N_a activities that we represent with a_i ($i = 1..N_a$). We distinguish **primary activities** from **secondary activities**. Primary ones are those activities that are of main importance in a given plan; in the case of the energy plan, primary activities are all those activities that directly produce energy, namely renewable and non-renewable power plants. Secondary activities are those supporting the primary ones by providing the needed infrastructures. We envisage the following type of inputs, directly linked to the notion of activity:

1. list of **primary activities** (e.g., Biomass plants, photovoltaic plants, wind mill plants, etc.) and, possibly, **minimal/maximal amounts for each activity** (e.g., increase by 10% the amount of photovoltaic energy);
2. **cost function**: we have a vector of costs $\mathbf{C} = (c_1, \dots, c_{N_a})$ where each element is associated to a specific activity and represents the cost per unit of that activity. Basically, we have to determine the cost for each MWatt of energy produced depending on the activity[1];
3. **efficiency function**: we have a vector of outcomes $\mathbf{Out} = (out_1, \dots, out_{N_a})$ to determine the energy produced by each installed MWatt of each activity; this function depends on the place (for instance in the south of Italy where the weather is sunny very often, the efficiency of photovoltaic is higher than in northern regions);
4. the **Primary-Secondary Activity matrix** $\mathcal{D}$, that is used to determine, for (the amount of) each activity, which (and how much of) secondary activities are required. Therefore we have a matrix of dependencies between activities. In particular we have 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.

Each activity impacts on one or more *receptors*. We will consider this part in the Strategic Environmental Assessment section.

Each region like, for example, Emilia-Romagna, has its own peculiar objectives. Some of them are intrinsically determined by the region itself, while others have a more political nature, and are the consequence of political decisions. In Figure 2 such inputs are depicted on the right of the DSS.

[1] The cost of a plant depends mainly on the installed power: a solar plant has an installation cost that depends on the square meters of installed panels, which in their turn can provide some maximum power (peak power). Notice that the considered cost is the total cost of the plant for the regional system, which is not the same as the cost for the taxpayers of the Emilia-Romagna region. Indeed, the region can enforce policies in many ways, convincing private stakeholders to invest in power production. This can be done with the financial leverage, or by giving favourable conditions (either economic or other) to investors. Some power sources are economically profitable, so there is no need for the region to give subsidies. For example, currently in Italy biomasses are economically advantageous for investors, so privates are proposing projects to build biomasses plants. On the other hand, biomasses also produce pollutants, they are not always sustainable (for a discussion on the issue, see [3]) so local committees are rather likely to spawn against the construction of new plants. For these reasons, the number of licenses the region gives to private stakeholders for building biomass-based plants are limited.

1. **required/expected outcome**: in an energy plan the outcome is the total energy to be expected within the regional boundaries, usually based on some estimation about the energy consumption;
2. **budget constraints**: each region has a total amount of funds available to be used as incentives for driving the energy market towards the desired direction; given a budget bud_{Plan} available for a given plan, a constraint limits the overall plan costs. This constraint can be posted either on the overall plan, or on parts of it. For instance suppose the budget has already been partitioned into chapters, then it would be possible to impose the above constraint only on activities related to a given chapter;

3. **political objectives**, provided by politicians. For example, a possible (political) priority is to be conformant with European guidelines such as the 20-20-20 initiative[2]. Such objectives could be translated into constraints on the minimum amount of energy produced by renewable energy sources.

Finally there are inputs related to the geo-physical configuration of the region and to best practices.

1. **energy source diversification**: the trend to allocate funds should not be directed toward a single energy source, but should cover various energy sources. This requirement comes as a best practice, and is supported by several considerations. For example, to be "robust" w.r.t. fluctuations of the price and availability of the various resources. Such input can be considered to be in the form of a constraint about the minimal percentage of the total energy needed to be produced by each energy source.
2. **social and geographic limits**: each region has its own geo-physical characteristics. For instance, some regions are particularly windy, while some others are not. Hydroelectric power plants can be built with a very careful consideration of environmental impacts, the most obvious being the flooding of vast areas of land. This poses constraints on the maximum energy that can be produced by a given energy source.

2.1 The Strategic Environmental Assessment

The policy maker also has to take into account impacts on the environment, economy and society, as defined by a Strategic Environmental Assessment that relates activities defined in the plan to environmental and economic impacts [3] . One of the instruments used for assessing a regional plan in Emilia-Romagna are the so called *coaxial matrices* [2], that are a development of the network method [28].

Each activity has impacts on the environment in terms of **positive** and **negative pressures**: an example of positive pressure is the increased availability of energy, while a

[2]The 20-20-20 initiative aims to achieve three ambitious targets by 2020: reducing by 20% its greenhouse gas emissions, having a 20% share of the final energy consumption produced by renewable sources, and improving by 20% its energy efficiency.

[3]Currently, the Strategic Environmental Assessment (SEA) is performed *a-posteriori*, when the plan has already been approved. ePolicy advocates the needs for using the SEA during the planning activity.

negative pressure is the production of pollutants. Pressures are themselves linked to **environmental receptors** such as the quality of the air, or of the surface water. On both pressures and receptors there are constraints, such as for example a constraint stating the maximum amount of greenhouse gas emissions of the overall plan.

One matrix $\mathcal{M}$ defines the dependencies between the above mentioned activities contained in a plan and positive and negative *impacts* (also called *pressures*) on the environment. Each element m_{ij} of the matrix $\mathcal{M}$ defines a qualitative dependency between the activity i and the negative or positive impact j. The dependency can be `high`, `medium`, `low` or `null`. Examples of negative impacts are energy, water and land consumption, variation of water flows, water and air pollution and so on. Examples of positive impacts are reduction of water/air pollution, reduction of greenhouse gas emission, reduction of noise, natural resources saving, creation of new ecosystems and so on.

The second matrix $\mathcal{N}$ defines how the impacts/pressures influence environmental *receptors*. Each element n_{ij} of the matrix $\mathcal{N}$ defines a qualitative dependency between the negative or positive impact i and an environmental receptor j. Again the dependency can be `high`, `medium`, `low` or `null`. Examples of environmental receptors are the quality of surface water and groundwater, quality of landscapes, energy availability, wildlife wellness.

Example 1 *The matrices currently used by ARPA for the SEA for the region Emilia-Romagna contain 93 activities, 29 negative impacts, 19 positive impacts and 23 receptors and assess 11 types of plans. Such matrices are used to evaluate how primary activities affect receptors, taking into account also secondary activities needed by primary ones (as specified by a* 93×93 *matrix D). The evaluation of how secondary activities affect receptors does take into account also the fact that some secondary activities are needed during the implementation of the primary ones, while others are needed while the functioning of primary activities.*

Although the energy plan and the environmental assessment are tightly related, their formulation is done independently. More precisely, there are a number of issues about the definition of the plan:

1. the regional planning activity is now carried on by human experts that build a single plan, considering regional objectives, and national and EU guidelines. No computer based techniques are exploited in this phase.
2. The agency for environmental protection is asked to assess the plan from an environmental point of view only after the plan has been devised. Typically, there is no (or very limited) feedback on the plan: the assessment can state that the devised plan is environmentally friendly or not, but it cannot change the plan. In some cases, it can propose corrective countermeasures, that can only mitigate the negative impact of wrong planning decisions.
3. Although regulations state that a significant environmental assessment should compare two or more options (different plans) this is rarely done, in Italy as well as in Europe.

2.2 Expected Outputs from the planning activity

Roughly speaking, the ultimate goal of an energy plan is to drive the free market of energy production towards the covering of the regional's energy requirements, and to achieve some political objectives. To this end, an energy plan consists of a set of *decisions* about the following aspects:

1. which types[4] (activities) of energy production systems should be employed, and for each of them their magnitude;
2. how much money will be assigned to push the market (through incentives) towards the desired production of energy, as identified in the previous point. This decision can be split up into two different sub-issues:
   (a) the amount of money to be allocated for pushing each different energy production system type, in the form of incentives;
   (b) the mechanisms for assigning such incentives (e.g., auctions)

As the second point is tightly related with the integration of the social simulator with the global optimizer, we consider in this deliverable only the first outcome.

From a mathematical perspective, a policy maker has a set of variables, and it is her duty to assign values to such variables. Variables represent decisions that have to be taken. For example, we could have a vector of activities $\mathbf{A} = (a_1, \ldots, a_{N_a})$. For each activity the policy maker decides also its magnitude $Mag_i, i \in [1..N_a]$. The magnitude could be represented in two ways: in an absolute way, as the amount of a given activity, or in a relative way, as a percentage with respect to the existing quantity of the same activity. In this document we adopt the absolute representation.

3 Use case scenario #1: the RER energy plan 2011-2013

In Deliverable 2.1 we proposed two use case scenarios, the second being concerned also with incentives and implementation instruments. In this deliverable we consider only the first one. The Energy Plan of the Emilia-Romagna Region, for the 2011-2013 years, has been published in 2011, and it is publicly available in [20]. The data presented in this Section have been taken from [20], or have been directly provided by RER employees.

The following inputs have been taken into consideration when preparing the energy plan:

Primary activities and minimum quantity : The primary activities that have been identified are:

1. Hydroelectric, with a minimum amount of installed power of 3 MW;
2. Photovoltaic, with a minimum of 400 MW;
3. Thermodynamic Solar Power, with a minimum of 5 MW;
4. Wind generations, with a minimum of 20 MW;
5. Biomasses power plants, with a minimum of 100 MW;

Function cost : This function provides the estimated cost to realize a certain type of energy production plant. These figures do not comprise the costs related to the functioning of the production plant, but only the costs for realizing the plant.

[4]To be precise, the types of energy are also influenced by some political objectives, that are given in input.

1. Hydroelectric: 8,400,000€/MW;
2. Photovoltaic: 3,500,000€/MW;
3. Thermodynamic Solar Power: 4,500,000€/MW;
4. Wind generations: 2,000,000€/MW;
5. Biomasses power plants: 3,500,000€/MW;

Efficiency Function of each activity This function provides the link between the installed power and the estimated produced energy (in TOE). The function has been estimated considering current technologies, and may vary over the years as the technology advances.

1. Hydroelectric: 0.2235483871 TOE/MW;
2. Photovoltaic: 0.1031764706 TOE/MW;
3. Thermodynamic Solar Power: 0.1 TOE/MW;
4. Wind generations: 0.12875 TOE/MW;
5. Biomasses power plants: 0.602 TOE/MW;

Primary-Secondary activity matrix This input has been provided by environmental experts and is contained in Deliverable 2.1.

Environmental Impacts This input has been provided by environmental experts and is contained in Deliverable 2.1.

Economic Impacts This input has not been taken into consideration for the current energy plan.

Social Impacts This input has not been taken into consideration for the current energy plan.

Total amount of energy to be produced In the current plan, the total amount of energy to be produced from renewable sources, for the year 2013, will be approximatively about 529.5 kTOE.

Budget constraints This input has not been taken into consideration for the current energy plan.

Feedback about mechanisms and incentives This input has not been taken into consideration for the current energy plan.

Political Objectives The current plan has been defined taking into account the "20-20-20" goal. Once energy requirements for 2013 have been estimated from previous trends about energy consumption, the "20-20-20" goal has been taken into account, thus establishing the energy amount to be achieved by efficiency, and the final quantity (20%) of energy to be produced from renewable sources. Given the current energy production figures (both renewable and non), the amount of energy to be produced has been decided (529.5 kTOE, as mentioned above). Summing up, the current energy plan has been "built" around a political objective: however, there is no reason to consider such link as to be the default for the future energy plans. It is sure that political objectives will provide some lower/upper bounds for renewable sources.

Energy source Diversification This input has been provided by RER experts.

Social and geographic limits This input has been provided by RER experts.

Incentives and mechanisms This input has not been taken into consideration for the current energy plan.

In the following we provide three approaches to the environmental assessment by using three models for representing coaxial matrices; as it will be clear, we chose the third as the model adopted in this project. On top of this model we will propose the planning component.

4 Environmental assessment with Causal Probabilistic Logic Programming

In this section we first present Probabilistic Logic Programming and then we discuss how to model causation with it.

4.1 Background on Probabilistic Logic Programming

The integration of logic and probability has been widely studied in Logic Programming and various languages semantics have been proposed, such as Probabilistic Logic Programs [5], Independent Choice Logic [19], PRISM [25], pD [10], CLP(BN) [4] and ProbLog [7].

Logic Programs with Annotated Disjunctions (LPADs) [30] are particularly suitable for reasoning about causes and effects [31]. They extend logic programs by allowing clauses to be disjunctive and by annotating each atom in the head with a probability. A clause can be causally interpreted by supposing that the truth of the body causes the truth of one of the atoms in the head non-deterministically chosen on the basis of the annotations.

An LPAD theory T consists of a finite set of *annotated disjunctive clauses*. These clauses have the following form

$$(H_1 : \alpha_1) \vee (H_2 : \alpha_2) \vee \ldots \vee (H_h : \alpha_h) : -B_1, B_2, \ldots B_b$$

where the H_is are logical atoms, the B_is are logical literals and the α_is are real numbers in the interval $[0, 1]$ such that $\sum_{i=1}^{h} \alpha_i \leq 1$. If $\sum_{i=1}^{h} \alpha_i < 1$, the head of the clause implicitly contains an extra atom $null$ that does not appear in the body of any clause and whose annotation is $1 - \sum_{i=1}^{h} \alpha_i$. If C is the clause above, $H(C, i)$ is H_i, $\alpha(C, i)$ is α_i and $body(C)$ is $B_1, B_2, \ldots B_b$.

The semantics of a non-ground theory T is defined through its grounding $g(T)$, and [30] requires that $g(T)$ is finite.

An *atomic choice* χ is a triple (C, θ, i) where $C \in T$, θ is a substitution that grounds C and $i \in \{1, \ldots, n\}$ where n is the number of atoms in the head of C. (C, θ, i) means that, for the ground clause $C\theta$, the head $H(C, i) : \alpha(C, i)$ was chosen. A *selection* σ is a set of atomic choices such that for each clause $C\theta$ in $g(T)$ there exists one and only one atomic choice (C, θ, i) in σ. We denote the set of all selections of a program T by $\mathcal{S}_T$.

A selection σ identifies a normal logic program $T_\sigma = \{(H(C, i) : -body(C))\theta | \, (C, \theta, i) \in \sigma\}$ that is called an *instance* of T. A probability distribution is defined over the space of instances by assuming independence among the choices made for each clause, thus the probability P_σ of an instance T_σ is given by

$$P_\sigma = \prod_{(C,\theta,i)\in\sigma} \alpha(C,i).$$

The meaning of the instances of an LPAD is given by the well-founded semantics [29]. For each instance T_σ, we require that its well-founded model $WF(T_\sigma)$ is total, since we want to model uncertainty only by means of disjunctions.

The probability of a formula Q is given by the sum of the probabilities of the instances in which the formula is true according to the well-founded semantics:

$$P(Q) = \sum_{\sigma\in\mathcal{S}_T, WF(T_\sigma)\models Q} P_\sigma$$

An LPAD T can be translated into a Bayesian network $\beta(T)$ that has a Boolean random variable for each ground atom plus a random variable $choice_{C\theta}$ for each grounding $C\theta$ of each clause C of T.

$choice_{C\theta}$ assumes value $H(C,i)\theta$ with probability $\alpha(C,i)$ if the configuration of its parents makes the body true, while it assumes value $null$ with probability 1 if the configuration makes the body false. A ground atom A has as parents all the $choice_{C\theta}$ variables for which A appears in the head of $C\theta$. A assumes value true with probability 1 if one of the parent choice variables assumes value A, otherwise it assumes value false with probability 1.

Various approaches have been proposed for computing the probability of queries from an LPAD. Riguzzi [22] discusses an extension of SLG resolution, called SLGAD, that is able to compute the probability of queries by repeatedly branching on disjunctive clauses. A different approach was taken by Meert et al. [16], where an LPAD is first transformed into its equivalent Bayesian network and then inference is performed on the network using the variable elimination algorithm. Riguzzi [21] presents the `cplint` system that first finds explanations (sets of atomic choices) for queries and then computes the probability by means of Binary Decision Diagrams, as proposed in [7] for the ProbLog language. `cplint` was used in the experiments in Section 4.3 because of its speed [23].

4.1.1 Causal Models

Determining when an event causes another event is very important in many domains, take for example science, medicine, pharmacology or economics. Causality has been widely debated by philosophers and statisticians: often it has been confused with correlation, while they are in fact distinct concepts, since two events may be correlated without one causing the other. Recently, [18] helped to clarify the concept of causation by discussing how to represent causal information and how to perform inference from it. [18] illustrates two types of causal models: causal Bayesian networks and structural equations.

Causal Bayesian networks differ from standard Bayesian networks because the edge from variable X to variable Y means that X is a cause for Y, while in standard Bayesian networks it simply means that there is a statistical dependence.

Pearl [18] proposed an approach for computing the probability of effects of actions and suggested to use the notation $P(y|do(x))$ to indicate the effect of the action of setting the variable X to value x on the event of variable Y taking value y. $P(y|do(x))$ is different from the probability of y given x ($P(y|x)$) because we do not simply observe $X = x$ but we intervene on the model by making sure $X = x$ is true.

The technique proposed in [18] for computing $P(y|do(x))$ consists of removing the parents of X, setting X to x and computing $P(y)$ in the obtained network.

This approach can be applied to probabilistic logic languages that can be translated to Bayesian networks, such as LPADs. In order to compute the probability of a ground atom Y of being true given an intervention that consists of making a ground atom X true from an LPAD T, we need to remove X from the head of all the clauses that contain it and by adding X as a fact to T. The probability of Y can then be computed from the resulting LPAD T' by using standard inference, i.e., by computing $P(Y)$.

4.2 A Causal Model for Environmental Assessment

In this section we provide an interpretation of Coaxial Matrices in a probabilistic sense. We associate to each activity, impact and receptor, a Boolean random variable and we consider the interaction levels expressed in the matrix as probabilistic causal dependencies. In this approach, we assume that an activity is either carried out or not, an impact is either present or not and a receptor is either achieved or not. In other words, we do not consider the magnitude or level of the variables under analysis. We used this approximation to get useful insights on the probabilistic modeling of the problem. In the future, we plan to consider more refined approximations with multivalued random variables or even continuous random variables.

Activities, impacts and receptors are represented by LPAD atoms (propositions) and the effects of activities on impacts and of impacts on receptors are expressed by means of LPAD rules that represent the Coaxial Matrices.

The model thus contains rules that express the effect of the activities on the environmental pressures (where m^i_j is an element of the $\mathcal{M}$ matrix):

$$pressure_j : m^i_j \text{ :- } activity_i.$$

Also, there are rules expressing the effect of the activities on the positive impacts:

$$positive\_impact_j : m^i_j \text{ :- } activity_i.$$

For example, the model contains the rule

```
'Dispersion of dangerous materials':0.75 :-
  'External movements of dangerous materials'.
```

that relates an activity and a pressure, and the rule

```
'Creation of work opportunities':0.5 :-
  'External movements of dangerous materials'.
```

that relates an activity and a positive impact.

Pressures reduce the probability of receptors, while positive impacts increase it. However adding a clause with a certain atom in the head can only increase the probability of the atom. To model the fact that pressures lower the probability of receptors, we use, for each receptor $receptor_k$, two auxiliary predicates $receptor\_pos_k$ and $receptor\_neg_k$ that collect the evidence in favor or against the achievement of the receptor.

The rules that express the negative effect of the pressures on the receptors take the form:

$$receptor\_neg_k : n_k^j \text{ :- } pressure_j.$$

while the rules that express the positive effect of the positive impacts on the receptors take the form:

$$receptor\_pos_k : n_k^j \text{ :- } positive\_impact_j.$$

where n_k^j is an element of the $\mathcal{N}$ matrix. For example, the rule

```
'Human health/wellbeing_neg':0.25 :-
  'Dispersion of dangerous materials'.
```

expresses a negative effect of a pressure on a receptor, and the rule

```
'Human health/wellbeing_pos':0.75:- 'Creation of work opportunities'.
```

expresses a positive effect of a positive impact on a receptor.

Finally, the positive and negative evidence regarding the receptor are combined with the following rules[5]:

$$\begin{array}{lll} receptor : 0.1 & \text{:-} & \backslash+ \, receptor\_pos, receptor\_neg. \\ receptor : 0.5 & \text{:-} & \backslash+ \, receptor\_pos, \ \backslash+ \, receptor\_neg. \\ receptor : 0.5 & \text{:-} & receptor\_pos, receptor\_neg. \\ receptor : 0.9 & \text{:-} & receptor\_pos, \ \backslash+ \, receptor\_neg. \end{array}$$

For example, the model contains the rules

```
'Human health/wellbeing':0.1 :- \+ 'Human health/wellbeing_pos',
                                   'Human health/wellbeing_neg'.
'Human health/wellbeing':0.5 :- \+ 'Human health/wellbeing_pos',
                                \+ 'Human health/wellbeing_neg'.
'Human health/wellbeing':0.5 :-    'Human health/wellbeing_pos',
                                   'Human health/wellbeing_neg'.
'Human health/wellbeing':0.9 :-    'Human health/wellbeing_pos',
                                \+ 'Human health/wellbeing_neg'.
```

[5]Where the symbol \+ stands for negation as failure, as usual in Prolog syntax.

that collect positive and negative effects on the receptor *"Human health/wellbeing"*.

These rules express the fact that *"Human health and wellbeing"* is unlikely if there is no positive evidence on it and there is negative evidence on it (first rule). It is very likely if there is positive evidence on it and no negative evidence on it (last rule). In the other cases, the probability of *"Human health and wellbeing"* is in between (second and third rule).

All the parameters were subjectively estimated and validated by the expert.

4.3 Evaluating the Causal Model

Given the causal model presented in Section 4.2, we can ask various what-if queries

1. if these activities are performed, what is the probability of a certain pressure or of a positive influence of appearing?
2. if these works are performed, what is the probability of a certain receptor being satisfied?

Queries of type 2 are more interesting because they relate the works directly with their final effects of interest. However, they are also more complex to compute. Moreover, the queries above can be generalized to the case in which the activities are performed with a certain probability.

We can answer the queries above by following the approach described in Section 4.1.1: we add a fact for each activity that is carried out and we ask the probability of the query from the modified program.

We report on a number of queries together with their execution times on Linux machines with an Intel Core 2 Duo E6550 (2333 MHz) processor and 4 GB of RAM.

The probability of the pressure *"Dispersion of Dangerous Materials"* performing the activities *"External movements of dangerous materials"* and *"Internal movements of dangerous materials"* is 0.937500. The CPU time was below 10^{-6} seconds.

The probability of the receptor *"Human health/wellbeing"* given that we perform the activities *"External movements of dangerous materials"* and *"Internal movements of dangerous materials"* is 0.546915 and the query took 22.713 seconds.

If we perform the activity *"Industrial processing and transformation"* the probability of the receptor *"Human health/wellbeing"* is 0.474918, computed in 84.453 seconds. This query takes longer than the previous ones because the work *"Industrial processing and transformation"* has an impact on many more influences than *"External movements of dangerous materials"*, and *"Internal movements of dangerous materials"* and all these impacts must be combined to find the effect on *"Human health and wellbeing"*. To give the reader an idea of the complexity of this query, there are 655,660 explanations, 12,847,036 atomic choices appear in the explanations and 42 random variables are involved.

The probability of receptor *"Atmosphere quality, microclimate"* given the action *"Industrial processing and transformation"* is 0.360851. The CPU time was 0.02s.

If we add the activity *"Oil and gas extraction plants"* the probability of the receptor *"Atmosphere quality, microclimate"* lowers to 0.326481, computed in 6.852s

By adding the activity *"Fire extinguishing plants"* the probability of the receptor *"Atmosphere quality, microclimate"* rises to 0.454471, due to the positive effects of the last activity. The CPU time was 92.67 seconds.

As can be seen from the last three cases, increasing the number of activities increases the computation time, since we have to combine the effects of the different causes. The last query has 606,726 explanations, 10,973,022 atomic choices appear in the explanations and 36 random variables are involved.

5 Fuzzy and Many-Valued Logic for Regional planning and assessment

In this section, we propose four models based on fuzzy and multi-valued logic.

5.1 Background

After the introduction of the concept of fuzzy set [33] by Zadeh for modeling vague knowledge and partial degrees of truth, much work has been done in various research areas to apply the concept of fuzziness to existing fields, including formal logic. According to [17], the fuzzification of classical logic has the goal of "*...addressing the vagueness phenomenon ..., modelling it with truth degrees taken from an ordered scale ..., preserving as many properties of classical logic as possible*". Historically, two possible approaches have been adopted [17]: one, more mathematically oriented, belongs to the family of many-valued logics and is called fuzzy logic "in a narrow sense", while the other, fuzzy logic "in a broader sense", is closer to Zadeh's original definition and uses a softer approach.

"Fuzzy" many-valued logics are a truth-functional generalization of classical logic. Atomic predicates p/n are considered fuzzy relations, whose truth degree is given by their associated membership function μ_P. Thus predicates can have truth values in the range $L = [0, 1]$. In order to construct and evaluate complex formulas, logical connectives, quantifiers and inference rules (e.g. modus ponens) are generalized to combine truth degrees. For example, the conjunction operator can be defined using any *t-norm* $\star$, such as the minimum, the product or Łukasiewicz's norm. Likewise, the disjunctive connective is defined using an *s-norm* and the implication depends on the t-norm definition by residuation [12]. A rule

$$C \leftarrow_i A$$

then, can be used to entail a fact C with a degree of at least c, provided that a fact matching with A exists with degree $a > 0$ and that the implication $\leftarrow$ itself has a degree $i > 0$.

In [33], Zadeh introduced the concept of *fuzzy linguistic variable*, a qualitative construct suitable to describe the value of a quantitative variable X with domain Δ_X. Each linguistic value λ_j belongs to a finite domain Λ and is associated to a fuzzy set A_j. Together, the sets define a fuzzy partition of Δ_X iff

$$\forall x \in \Delta_X : \sum_j \mu_{A_j}(x) = 1.$$

The membership values of an element x to a set can either be interpreted as the *compatibility* of x with the concept expressed by a linguistic variable, or as the *possibility* that x is the actual value of X, assuming that x is unknown save for the fact that it belongs to A_j. (For a complete discussion on the relation between compatibility and possibility, see [9]).

Fuzzy partitions are usually used in conjunction with fuzzy rules to approximate complex functions $y = f(x)$ by fuzzifying the function's domain and range, then matching the resulting input and output sets using rules [8]. Different types of rules have been proposed: "Mamdani" rules infer fuzzy consequences from fuzzy premises and have the form

$$x\ is\ A_j \ \Rightarrow_\varepsilon \ y\ is\ B_k$$

where A_j and B_k are fuzzy sets and is is the operator evaluating set membership. Fuzzy Additive Systems (FAS), instead, entail quantitative values, and adopt rules such as

$$x\ is\ A_j \ \Rightarrow_\varepsilon \ y = y_r$$

(wherey_r is a value). In the former case, then, it is necessary to collect the different sets entailed by the various rules, combine them - usually by set union - into a single possibility distribution and finally, if appropriate, apply a defuzzification process [24] to get a crisp consequence value. In the latter case, instead, the quantitative values are directly available and can be aggregated, e.g., using a linear combination.

There are two main approaches for representing each variable (activity, pressure or receptor) in our model. The first is to define a many-valued predicate, $mag/1$, whose truth value represents the magnitude of that variable, i.e. represents how much the considered variable is "large" in terms of a truth value in the interval $[0, 1]$. Notice that, although the predicate is the same, the membership function is different for each variable. For example, if we have the activity *road construction* and atom $mag(road)$ has truth value 0.7, this means that the plan involves the building of a significant amount (0.7) of roads with respect to the current situation, while a smaller truth value would correspond to a smaller number of kilometers of roads to be built.

In the second approach, a fuzzy linguistic variable is defined for each variable, creating a fuzzy partition on its domain. The partition contains one fuzzy set for each value of the linguistic variable. The sets are used to describe different levels of magnitude: we consider a five-set fuzzy partition of each variable's domain consisting of the sets *VeryLow*, *Low*, *Average*, *High* and *VeryHigh*.

The second degree of freedom we have is the selection of the aggregation method for the results, i.e. the choice of the s-norm used to combine the results of the application of rules with the same consequent. For example, consider two pressures such as energy consumption and odor production; the overall energy consumption is the sum of the consumptions due to the single activities, but the same hardly applies to odor production. An activity that produces a strong odor may "cover" weaker odors, so a good aggregation for this kind of variable should be the maximum (or geometrical sum). The aggregation strategy becomes even more important in the case of environmental receptors.

Pressures can be either "positive" or "negative": translating positive pressures into positive contributions, and negative ones into negative contributions would be an approximation since the former do not always cancel the latter. If a linear model returns a final result of 0 for a given receptor, there is no way of telling whether that value is the combination of large positive and negative contributions canceling each other, or we are simply in the case of absence of significant pressures influencing that receptor. So, we have chosen to split the individual receptor variables into two parts, one considering only positive and one considering only negative pressures affecting that receptor. The strategy for the combination of the two can then be decided on an individual basis.

In the remainder of this section, we will provide a description of the four classes of models which can be designed, according to different combinations of the underlying logic (many-valued vs classical fuzzy) and aggregation style (linear vs non-linear), as shown in Figure 3.

	Lin.	**Non Lin.**
MVL	Model I	Model II
Fuzzy	Model IV	Model III

Figure 3: Model classification by type of logic and aggregation style.

5.2 Many-valued logic models

5.2.1 Model I

As a first attempt, we started from a constraint based model in terms of quantitative fuzzy concepts. This model takes as input the activities, in terms of their relative magnitudes, and calculates pressures as

$$p_j = \sum_{i=1}^{N_a} m_{ij} a_i.$$

Each coefficient m_{ij} quantifies the dependency between the activity i and the pressure j according to the qualitative value in the matrix M. The values $a_{i:1..N_a}$ are the magnitudes of each activity: the values represent the increment of an activity A_i as a percentage in relation to the existing A_i^0, in order to make the different activities comparable. For example, a magnitude of 0.1 for activity *"thermoelectric plants"* means increasing the production of electricity through thermoelectric energy by 10% with respect to the current situation.

Likewise, the influence on the environmental receptor r_k is estimated given the vector of environmental pressures $p_{j:1..N_p}$ calculated in the previous step. A formulation of the model in logic terms consists of the following Horn clauses:

$$contr(Press_j, Act_i) \Leftarrow_{\beta_{i,j}} mag(Act_i) \wedge impacts(Act_i, Press_j) \quad (1)$$

$$mag(Press_j) \Leftarrow_1 \exists\, Act_i : contr(Press_j, Act_i) \quad (2)$$

where we use the auxiliary predicate *contr* to describe the contribution from a single source, whereas *mag* describes the aggregate contributions.

The value $\beta_{i,j}$ is a normalization coefficient, that makes the maximum possible value of truth for $mag(Press_j)$ equal to 1 when the truth degree of $mag(Act_i)$ for all the impacting activities is equal to 1. Its default value can be changed by the environmental expert to obtain other behaviors.

In order to replicate the behavior of a linear model, we need to

1. configure the $mag/1$ predicate to use a linear membership function,
2. configure the $impacts/2$ predicate to use a membership function derived directly from the matrix, i.e.

   $$\mu_{impacts(Act_i, Press_j)} = m_{ij}$$

   where m_{ij} is a real value obtained from the qualitative dependencies
3. configure the $\wedge$ operator to use the product t-norm,
4. configure the $\exists$ quantifier to use a linear combination s-norm and (v) configure the reasoner to use gradual implications and the product t-norm to implement modus ponens.

The critical point is that the logic operators do not aggregate values, which have only a quantitative interpretation, but degrees of truth, which have a more qualitative interpretation. If one wants the degree to be proportional to the underlying quantitative value, the use of scaling coefficients might be mandatory since a degree, having an underlying logic semantics, is constrained in $[0, 1]$. Intuitively, the coefficients model the fact that, even if an individual piece of evidence is true, the overall proof may not: the coefficient, then, measures the loss in passing from one concept to the other (which, from a logical point of view, is a gradual implication). If the coefficients are chosen accurately, the aggregate degree becomes fully true only when all the possible contributions are fully true themselves. As a side effect, the normalization function used by the predicate $mag/1$ cannot map the existing amount A_i^0 of a given activity to 1, since that is not the theoretical maximum of a new activity, and the contributions of the individual activities require a scaling by a factor $\beta_{i,j}$ before being aggregated.

5.2.2 Model II

After a more detailed discussion with the expert, however, it turned out that no single model alone — qualitative or quantitative, linear or non-linear — could capture the full complexity of the problem, mainly because the relations between the entities are different depending on the actual entities themselves.

A purely linear model has also other limitations: for example, some public works are already well consolidated in the Emilia Romagna region (e.g. roads), so that even a large scale work would return a (linearly) normalized activity value around 1. Others, instead, are relatively new and not well developed (e.g. wind plants), so even a small actual amount of work could yield a normalized value of $5 \div 10$, unsuitable for logic modelling as well as being unrealistic given the original intentions of the experts. In order to cope with this problem, we decided to adopt a non-linear mapping between the amount of each activity and its equivalent value, using a sigmoid function:

$$a_i = \frac{1 - e^{-A_i/(k_i A_i^0)}}{1 + e^{-A_i/(k_i A_i^0)}} \tag{3}$$

This expression behaves like a linear function for small relative magnitudes, while saturates for larger values, not exceeding 1. The relative magnitude can be further scaled using the parameter k_i, provided by the expert, to adjust the behaviour for different types of activities. Moreover, the normalization function (3) is a proper membership function for the fuzzy predicate $mag/1$, defining how large the scale of an activity is with respect to the existing and using the parameter k_i to differentiate the various entities involved.

This membership function, however, also slightly changes the semantics of the linear combination. In Model I, we had a sum of quantitative elements, measured in activity-equivalent units and weighted by coefficients derived from the matrix. Now, instead, we have a proper fuzzy count[6] of the number of activities which are, at the same time, "large" and "impacting" on a given pressure. Notice, however, that we still need gradual implications, in order to use the standard, "*or*"-based existential quantifier to aggregate the different contributions.

The second extension we introduce in this model involves the relation between pressures and receptors. While in Model I it is sufficient to replicate rules (1) and (2), here we keep the positive and negative influences separated:

$$\begin{aligned}
contrPos(Press_j, Rec_k) &\Leftarrow_{\gamma_{j,k}} mag(Press_j) \wedge impactsPos(Press_j, Rec_k)\\
contrNeg(Press_j, Rec_k) &\Leftarrow_{\delta_{j,k}} mag(Press_j) \wedge impactsNeg(Press_j, Rec_k)\\
\mathit{influencePos}(Rec_k) &\Leftarrow_1 \exists\, Press_j : contrPos(Press_j, Rec_k)\\
\mathit{influenceNeg}(Rec_k) &\Leftarrow_1 \exists\, Press_j : contrNeg(Press_j, Rec_k)
\end{aligned}$$

In order to combine the positive and negative influences, their relation has to be expressed explicitly. For example, rule (4) states that positive and negative influences are interactive and affect each other directly; rule (5) defines the concept of beneficial pressures explicitly, while rule (6) stresses those receptor which have been impacted in an absolute way. As usual, the operator definitions can be chosen on a case-by-case basis to better model the

[6]The cardinality of a fuzzy set is the fuzzy count of its elements, computed as the sum of the membership degrees of its elements.

relations between the particular pressures and receptors.

$$influencePos(Rec_k) \;\Leftrightarrow_\varepsilon\; \neg\, influenceNeg(Rec_k) \tag{4}$$

$$benefit(Rec_k) \;\Leftarrow_1\; influencePos(Rec_k) \wedge \neg\; influenceNeg(Rec_k) \tag{5}$$

$$hit(Rec_k) \;\Leftarrow_1\; influencePos(Rec_k) \vee influenceNeg(Rec_k) \tag{6}$$

5.3 Fuzzy Models

In models I and II, the elements of the coaxial matrices are converted into simple scaling coefficients. To increase the expressiveness of this mapping, we assumed that each label is actually an indicator for some kind of predefined function, for which we do not provide an analytic expression, but a fuzzy logic approximation [8]. So, we created fuzzy partitions on the domain of each activity, pressure and receptor: in particular, each partition consists of 5 triangular membership functions, not necessarily equally spaced on the domains. These sets have been associated to the linguistic values *VeryLow*, *Low*, *Average*, *High* and *VeryHigh*. Then, we used rules such as $VeryLow(Act) \Rightarrow VeryLow(Pres)$ to map (linguistic) values from one domain onto (linguistic) values of the corresponding range, according to the connections expressed in the matrices.

In both models III and IV we give the same interpretation to the matrix elements, using linear functions with slope 1, 0.5 and 0.25 for "*high*", "*medium*" and "*low*" respectively. These functions, then, are fuzzified as shown schematically in Figure 4. A *VeryHigh* input is mapped onto a *VeryHigh*, *Average* or *Low* output, respectively, when the label in a cell of a coaxial matrix is *high*, *medium* or *low*. The mapping can easily be changed by altering the rules and allows one to define non-linear relations as well as linear ones. In fact, the use of a fuzzy approximation gives a higher flexibility to the system, while keeping the evaluation robust.

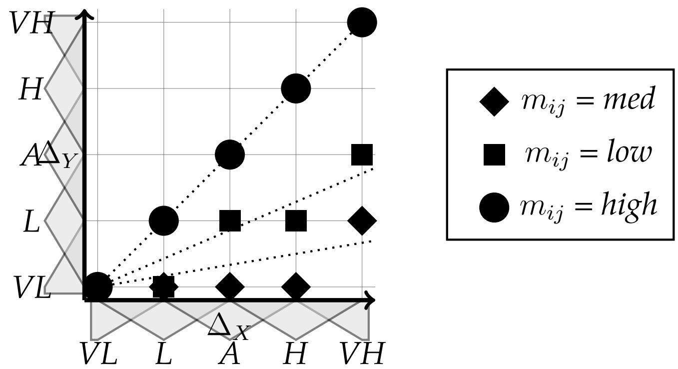

Figure 4: Relation between an activity a_i and a pressure p_j depending on the value m_{ij} appearing in the coaxial matrix.

5.3.1 Model III

Model III is a canonical fuzzy system, where the relations between

- activities and pressures and

- pressures and positive and negative effects on receptors

are defined using fuzzy rules. The inputs, the activities' magnitudes, are no longer normalized, but fuzzified: the rules are then evaluated using the min-max composition principle [8] and chained, propagating the inferred fuzzy distributions from the pressures onto the receptors. If needed, the resulting possibility distributions can then be defuzzified to obtain a crisp "impact" value for each receptor. Using this model, it is possible to distinguish pressures which are affected by the different activities at different levels.

5.3.2 Model IV

According to the experts, however, Model III suffers from a drawback: being purely qualitative, the degrees inferred for each fuzzy set tell only whether a pressure/receptor will *possibly* be affected with any level of intensity. Suppose for example that activity a_i generates pressure p_j with *Low* intensity. If the magnitude of a_i is sufficiently large, the system will entail that it is (fully) possible that p_j has a *Low* component. This answer is not quantitative: it would not allow us to distinguish this case from one where many different activities, all individually generating pressure p_j with low intensity, are present at the same time. Thus, this model is appropriate when only a qualitative answer is sufficient.

To overcome this limitation, we created Model IV as a minor extension of Model III, exploiting the same concepts used in Model II. We used gradual rules to scale and give an additional quantitative meaning to the consequence degrees:

$$VeryLow(Act) \Rightarrow_{\beta} VeryLow(Pres).$$

Then, we allowed the norms to be configurable, so the min-max composition principle was replaced by a more general t-s norm composition principle. The min-max model, now a special case, is still admissible and is suitable for situations where the various inputs are not interactive, whereas the probabilistic sum and the algebraic sum s-norms are more suitable when the sources are independent or exclusive.

5.4 Fuzzy Model Evaluation

We implemented the four models using the Jefis Library [32], and tested the software on a system equipped with a Core 2 Duo T6600 processor and 4GB RAM. Using the full content of the coaxial matrices to derive the rules and a past regional energy plan as a realistic test case, the evaluation required less than 1 second, guaranteeing that computation time is not a critical factor for the proposed system, considering also that the task is not to be performed in hard real time. Instead, we focus on the assessment of the expressiveness of the four models, to highlight their strengths and weakness. Here, for the sake of readability, we will discuss a more focused test case rather than a whole plan.

We assume that the matrices contain only two activities - *Incinerators* (INC) and *Wastewater Treatment Plants* (WTP), two pressures - *Noxious Gases Emission* (NG) and *Odour Emission* (OD), and one environmental receptor - *Landscape Quality* (LQ). In our example, the two activities influence both pressures, albeit in a different way. The first pressure, NG,

		Noxious Gases Emission	Odour Emission
Activities	Incinerators	H	M
	Wastewater Treat. Plants	M	H
Receptors	Landscape Quality	L	H

Table 1: Excerpt of the Coaxial Matrices

is assumed to be linear in the causes: different independent sources simply increase the amount of gas released into the atmosphere; the latter, OD, is not linear: since odors cover each other, we assumed the sources to be independent but interactive. Moreover, both pressures affect negatively the considered receptor, with an influence strength shown by the matrix excerpt in Table 1. When computing the effects of the pressures, instead, we assumed them to be independent and non-interactive, so the positive (respectively, negative) impact on the receptor is given by the best (resp. worst) effect induced by a pressure. Notice that only models II and IV are able to capture these differences, since model I is linear by default, and model III is non-interactive by default. Given this simplified matrix, the models were set up as follows. Regarding activities, we assume that the initial input is already expressed in terms of equivalent units: a planned magnitude of 100 units is equivalent to the currently existing amount of the same activity. In our test, we set $A_{INC} = 90$ and $A_{WTP} = 180$.

To perform a linear normalization in Model I, we assume that plans cannot involve values greater than 200, effectively planning the construction of no more than twice the existing. When the sigmoidal normalization is used in Model II, an upper limit is not necessary; however, for comparison purposes, we chose values for k_{INC} and k_{WTP} such that the result is the same as when the linear normalization is applied, i.e. the resulting normalized values are 0.45 and 0.9 respectively. Models III and IV, instead, do not require an explicit normalization, since it is performed implicitly by the fuzzification of the magnitudes. Since they are already expressed in equivalent units, all activities share the same domain - the range $[0..200]$, which has been partitioned using sets labelled *VL*, *L*, *A*, *H* and *VH*. All sets are uniformly spaced and use triangular membership functions, except *VH*, which uses a "right-shoulder" function, and *VL*, which uses a "left-shoulder" function. As already pointed out, in Model I and II the values of both matrices are mapped onto 0.75, 0.5 and 0.25; Model III and IV, instead, map the values onto different set of rules, as shown in figure 4. When evaluating the pressure NG, Model II and IV also use scaling coefficients $\beta = 0.5$ (i.e. the reciprocal of the number of activities) to avoid saturation.

We now discuss the evaluation of the different models. First, we consider the relation between INC, planned with magnitude 90, and NG, which is *high* according to the matrix.

1. Using rule (1) with the product norm, the linearly normalized magnitude, 0.45, is scaled by the coefficient 0.75, yielding a contribution of 0.3375.
2. Similarly, the sigmoidal normalization yields 0.45. This time, however, the gradual rule entails a pressure magnitude of 0.16875.

3. The fuzzification of the input yields a reshaped partition $\{L/0.75, A/0.25\}$ describing the magnitude of the activity. After the adequate set of rules has been applied, one obtains a contribution for the distribution of the pressure, which incidentally is identical: $\{L/0.75, A/0.25\}$.
4. The result is analogous in Model IV, save for the effect of the gradual rule: $\{L/0.375, A/0.125\}$

In order to compute the overall degrees for the pressure NG, one must also take into account the contributions due to the WTP activity, planned with magnitude 180: according to the coaxial matrix, the relation between the two is *medium*.

1. The second contribution, 0.9, is summed to the previous one, yielding 0.7875.
2. This model gives a contribution of 0.225. Depending on the chosen s-norm, this value is combined with the other value of 0.16875: since gas emissions are additive, we use Łukasiewicz's *or* to get a combined value of 0.39375.
3. The fuzzified input, $\{H/0.5, VH/0.5\}$, is mapped onto the output as $\{L/0.5, A/0.5\}$ due to the use of a different set of rules, in turn due to the relation between the two being defined as *medium*. The fuzzy union of the previous and current contributions gives $\{L/0.75, A/0.5\}$.
4. The combination of gradual fuzzy rules, and the use of Łukasiewicz's *or* leads to a final result of $\{L/(0.375 + 0.25), A/(0.125 + 0.25)\}$

The same procedure is repeated for OD. Notice that, due to the initial modelling assumptions, a more appropriate s-norm for models II and IV is the "probabilistic sum". Once both pressures have been evaluated, the inference propagation pattern is applied once more to obtain the final degree/distribution for the receptor LQ. Given the initial assumption of non-interactivity, the "max" s-norm would be more appropriate in models II and IV, however we performed the computations also using the bounded and noisy sum norms for comparison. All the intermediate and final results are reported in table 2. Notice that we only consider negative effects on the environmental receptor because all pressures considered in this example were considered as negative pressures.

5.5 Conclusions on the fuzzy models

We now drive some conclusions on the four models. They have different features and informative capabilities. Model I is an implementation of a linear model in fuzzy logic; it cannot distinguish interactive from non-interactive effects, and scenarios with many small effects from scenarios with a few large ones. Model II can cope with the former problem, but not with the latter, while Model III tackles the latter but not the former. Model IV combines the two aspects in a single model and was considered by the expert as the most expressive and informative. Moreover, instead of a precise single value, Model IV now proposes a possibility distribution over the values that can be expected for environmental receptors.

In this work we implemented the simple one-way relation included into the co-axial matrices already used in the Emilia-Romagna region. However, environmental systems are

		I	II	III	IV
Act	INC	0.45	0.45	$\{L/0.75, A/0.25\}$	$\{L/0.75, A/0.25\}$
	WWTP	0.90	0.90	$\{H/0.5, VH/0.5\}$	$\{H/0.5, VH/0.5\}$
Press	NG	0.79	0.39	$\{L/0.75, A/0.5\}$	$\{L/0.625, A/0.375\}$
	OD	0.90	0.72	$\{VL/0.75, L/0.25, H/0.5, VH/0.5\}$	$\{VL/0.75, L/0.25, H/0.5, VH/0.5\}$
Rec	$LQ^{-}_{\vee}$	0.87	0.54	$\{VL/0.75, L/0.25, H/0.5, VH/0.5\}$	$\{VL/0.75, L/0.25, H/0.5, VH/0.5\}$
	LQ^{-}_{+}	0.87	0.64	$\{VL/0.75, L/0.25, H/0.5, VH/0.5\}$	$\{VL/1.00, L/0.25, H/0.5, VH/0.5\}$
	$LQ^{-}_{\oplus}$	0.87	0.58	$\{VL/0.75, L/0.25, H/0.5, VH/0.5\}$	$\{VL/0.95, L/0.25, H/0.5, VH/0.5\}$

Table 2: Intermediate and final results of the evaluation.

very complex, and seldom relations are only in one direction, but environmental receptors could have an effect on the impacts or raise the need to perform some compensation activity in the future regional plans. In future work, we plan to study such effects.

6 CLP(R) model for Environmental Assessment

6.1 Constraint Logic Programming

Constraint Logic Programming (CLP) [14] is a class of programming languages which extend classical Logic Programming. Variables can be assigned either terms (as in Prolog), or interpreted values, taken from a *sort*, that is a parameter of the specific CLP language. For example, we can have CLP($\mathcal{R}$) [15], on the sort of real values, or CLP(FD), in which variables range on finite domains. The sort also contains interpreted functions (that, in numerical domains, can be the usual operations +, -, $\times$, etc.) and predicates (e.g., $<$, $\neq$, $\geq$, etc.), that are called *constraints*. The declarative semantics gives the intuitive interpretation of the specific sort to constraints and interpreted terms: e.g., $1.3 + 2 < 5$ is *true* in CLP($\mathcal{R}$). The operational semantics resembles that of Prolog for atoms built on the usual predicates (i.e., those predicates defined by a set of clauses), but stores the interpreted ones, the constraints, to a special data structure, called the *constraint store*. The store is then interpreted and modified by an external machinery, called the *constraint solver*. The solver is able to check if the conjunction of constraints in the store is (un)satisfiable, and is also able to modify the store, possibly simplifying it to a refined state. Usually, the constraint solver does not perform *complete* propagation: if it returns *false*, then there is definitely no solution, but in some cases it may fail to detect infeasibility even if no solution exists.

CLP($\mathcal{R}$) is the instance of CLP in which variables range on the reals. The set of available constraints are linear equalities and inequalities, and the solver is usually implemented through the simplex algorithm, that is very fast and is complete for linear (in)equalities (it always returns *true* or *false*). In some systems, given the availability of fast integer linear programming solvers, some nonlinear constraints are also accepted in the language, in particular the user can impose that some variables take only integer values. In this case, the complexity of the problem moves from P to NP-hard, and the solver often relies on some form of branch-and-bound. Also, the user can communicate to the solver an *objec-*

tive function: a linear term that should be minimized or maximized while satisfying all constraints.

Many implementations of CLP($\mathcal{R}$) exist nowadays [6], and many Prolog flavours [34, 13] have their own CLP($\mathcal{R}$) library. We decided to adopt ECL^{i}PS^e [1, 26], that features a library called *Eplex* [27]. This library interfaces ECL^{i}PS^e to an external mixed integer linear programming solver, that can be either a state-of-the-art commercial one (like CPLEX or Xpress-MP), or an open source solver. By default, Eplex hides most of the details of the solver, but nevertheless, when required, the user can trim various parameters to boost the performance, and also inspect the internals of the solver. This feature comes very useful in practical applications, and will be used to provide additional valuable information to the user, as detailed in Section 6.2.

6.2 Coaxial Matrices in CLP(R)

The coaxial matrices can be simply interpreted as a linear programming model. Amongst the many ways to invoke a linear programming solver, we decided to use CLP($\mathcal{R}$); in this way the model is written as a knowledge base in a computational logic language, that could be easier to integrate with the probabilistic approach in Section 4, or with the fuzzy approach in Section 5.

More in detail, we consider the values of the magnitudes (see Section 2.2) as a vector $\mathbf{A} = (a_1, \ldots, a_{N_a})$. Now, the environmental impacts caused by the activity i (with magnitude a_i) can be estimated with the system of linear equations

$$\forall j \in \{1, \ldots, N_p\} \quad p_j = m_j^i a_i.$$

When considering a whole regional plan, we sum up the contributions of all the activities and obtain the estimate of the impact on each environmental impact/pressure:

$$\forall j \in \{1, \ldots, N_p\} \quad p_j = \sum_{i=1}^{N_a} m_j^i a_i. \tag{7}$$

In the same way, given the vector of environmental pressures $\mathbf{P} = (p_1, \ldots, p_{N_p})$, one can estimate the influence on the environmental receptor r_i by means of the matrix $\mathcal{N}$, that relates pressures with receptors:

$$\forall j \in \{1, \ldots, N_r\} \quad r_j = \sum_{i=1}^{N_p} n_j^i p_i. \tag{8}$$

The system of equations (7-8) are imposed as constraints in a CLP($\mathcal{R}$) program; thanks to this formalisation, a number of queries of high interest both for the planner and for the evaluator of the environmental policy can be posed to the system as CLP($\mathcal{R}$) goals.

The final goal for the evaluator of the environmental policy is computing the environmental footprint of a devised plan. The plan is given as a set of values representing the magnitude of each of the activities. In other words, given the set of values $\mathbf{A} = (a_1, \ldots, a_{N_a})$, we can compute the environmental footprint $\mathbf{R} = (r_1, \ldots, r_{N_r})$, simply by applying equations (7) and (8).

Another query studies the impact of a single unit (in a standardized format) of activity a_i; for example, we are interested to know what is the environmental footprint of producing 1MW of electric power through a thermoelectric plant. We instantiate the vector of activities to a unary vector with $a_i = 1$ if $i = therm$ and $a_i = 0$ otherwise:

$$\mathbf{A} = (0, 0, \ldots, 1, \ldots, 0)$$

In this way, one can find out, by looking at the resulting vector $\mathbf{R}$, which of the receptors are (positively or negatively) influenced by the devised activity. Also, one can get an estimate of those receptors that are more heavily influenced, and those that are only marginally influenced. This query can be used by experts to calibrate the numbers in the coaxial matrices, by considering singularly each activity.

Another important query for the final user is asking which of the possible activities (always in normalized form) has a major impact on some given receptor r_i. In fact, in CLP($\mathcal{R}$), one can maximize or minimize some objective function, so the model becomes

$$\begin{array}{rc} & max(r_i) \\ s.t. & \text{(7)(8)} \\ & \sum_j a_j = 1 \\ & \forall j, a_j \text{ is integer} \end{array}$$

Finally, if there are laws imposing limits on some receptors (limits for CO_2, for example) one can very easily impose constraints on receptors (e.g., $r_{CO_2} \leq limit_{CO_2}$), and find if an activity can either be performed at all, or if it requires some compensation (e.g., another activity that improves on the receptor, like reforestation for CO_2), or if it can be done in association with other activities.

In cases where there are two or more alternative activities that cater for the same need, the regulations prescribe that alternatives should be studied, and compared. For example, the need for additional electrical power is satisfied by building a new plant; however one can choose the type of plant, depending on the environmental conditions. In an area with highly polluted air, a thermoelectric plant could raise the pollution over the law limit, so a different type of plant could be devised, like a solar power plant. On the other hand, a solar plant could be too expensive, and make unaffordable other activities that are necessary in the area (e.g., building a school, a hospital, etc.). In this case, the planner can impose a constraint stating that there is a regional need for at least k MW of electrical power; he/she imposes

$$\sum_{i \in PowerPlants} a_i \geq k$$

(where $PowerPlants$ is the set of indices in the vector $\mathbf{A}$ corresponding to those plants that provide electrical power) and then can optimize for one of the receptors, e.g., r_{CO_2}, or some weighted sum of receptors of interest. Or, the planner may ask what is the maximum power that can be generated in the region without violating the law limits on the receptors

$$
\begin{array}{lc}
 & max \sum_{i \in PowerPlants} a_i \\
s.t. & (7)(8) \\
\forall i \in \{1, \dots, N_r\} & r_i \leq limit_i
\end{array}
$$

In this way, we find the maximum number of MW that can be produced, as well as the electrical power produced by each type of plant. Note that in this way the solver could find an assignment that imposes the execution of compensation activities, as hinted earlier. If there are not enough resources for compensation, we can impose that such activities must not be performed (e.g., by assigning value 0 to all these activities), or we can impose that, given a vector **C** with the cost of each activity, the total cost of the activities should not be higher than the allotted finances F:

$$\sum_{i=1}^{N_a} c_i a_i \leq F \tag{9}$$

In the same way, other types of resources, like time, person-months, energy, can be taken into consideration.

We are currently improving the model to take into account the fact that different activities can have different impacts on the environment depending on the type of zone they are placed. For example, if we build a power line within a natural park, its impact is definitely higher than building it near a city. An additional feature we are studying is the fact that depending on the zone we are considering, different impacts might have different weights. For instance, the water quality is extremely important on a river delta, where the whole ecosystem relies on the river water, while it is less important in an industrialized area.

6.3 Sensitivity Analysis

The simplex algorithm provides the optimal value of the objective function, the optimal assignment to the decision variables, and also other information that is of high interest for the decision maker. In particular, it provides the so-called *reduced costs*, and the *dual solution*. These indicators provide precious information on the sensitivity of the found solution to the parameters of the constraint model.

The dual solution is a set of values that correspond to the constraints. It can be thought as the derivatives of the objective function with respect to the right hand side (RHS) of the constraints. This means that we immediately see, in the dual solution, which of the constraints are *tight*, i.e., which would change the value of the objective function if the RHS coefficient changes. For example, if we are optimizing the number f_{MW} of MW of electric power, and we have a constraint

$$r_{CO_2} \leq limit_{CO_2}$$

and the corresponding dual value d_{CO_2} in the optimal solution is non-zero, this means that

$$d_{CO_2} = \frac{\partial f_{MW}}{\partial limit_{CO_2}}.$$

In other words, the value of the dual variable d_{CO_2} answers to the question: *"How much would the production of energy decrease in case the limit of CO_2 lowers of one point?"* This is an important information, since regulations change, and tend to become more strict.

The same analysis can be performed on the problem of optimizing some (weighted sum of) receptors, given a total number of plants (or required MW). In this case, the dual value associated to a constraint represents how much the receptor will improve if that constraint is partially relaxed (if the RHS becomes less strict). For example, suppose we are optimizing the emissions of nitrogen oxides (NO_x), and we have the constraint (9) stating a limit on the total cost of the activities, for example, in euros. After obtaining the optimal value, the planner could ask: *"Suppose now that we had more money: if I add one euro, how much would the emissions of NO_x decrease?"* The answer is the dual value d_e of the constraint (9). This analysis is very attractive for the evaluator.

6.4 Experimental results of CLP(R)

ARPA Emilia-Romagna (the environmental protection agency of the Emilia-Romagna region, Italy) kindly provided us with the coaxial matrices used for assessing eleven types of plans (that we translate into the CLP model) and the data of a regional energy plan: for each of the activities, we have a *"magnitude"* value. Thanks to the CLP model described earlier, we are able to compute the corresponding values of pressures and receptors.

Initially the results were counterintuitive: the considered plan concerned energy (aimed at raising the available electrical power in the region), while the receptor *energy availability* had a lower value than the previous year. These types of results may be partially due to the qualitative information contained in the matrices, but also highlight possible human mistakes in the data of the matrices. Indeed, a flaw was found (and fixed) in the matrices, showing how logic-based decision support can contribute to increase the reliability of the environmental assessment.

Once the human mistakes had been corrected, we re-run the experiments. The new results were highly appreciated by the evaluator: the decision support system foresaw strong decrease of *quality of air* (mainly due to the boost on thermoelectric plants), and *water availability* (since thermoelectric plants need refrigeration).

As the plan had a large impact on some receptors, we tried to improve it from an environmental viewpoint: the magnitude of each of the activities was allowed to deviate up to 1% with respect to the original plan, and we optimized the *quality of air* receptor. We had an improvement of about 20.3% on this receptor, which shows that even by allowing small variations one can get significant improvements. On the other hand, we had a decrease of industrial indicators, such as the *availability of productive resources* or the *availability of energy*.

We also tried two dual goals. The first considers the given plan, keeps constant all activities except the building of (various types of) power plants, fixes the amount of produced energy, and tries to optimize on the quality of air. The second, instead, maximises the

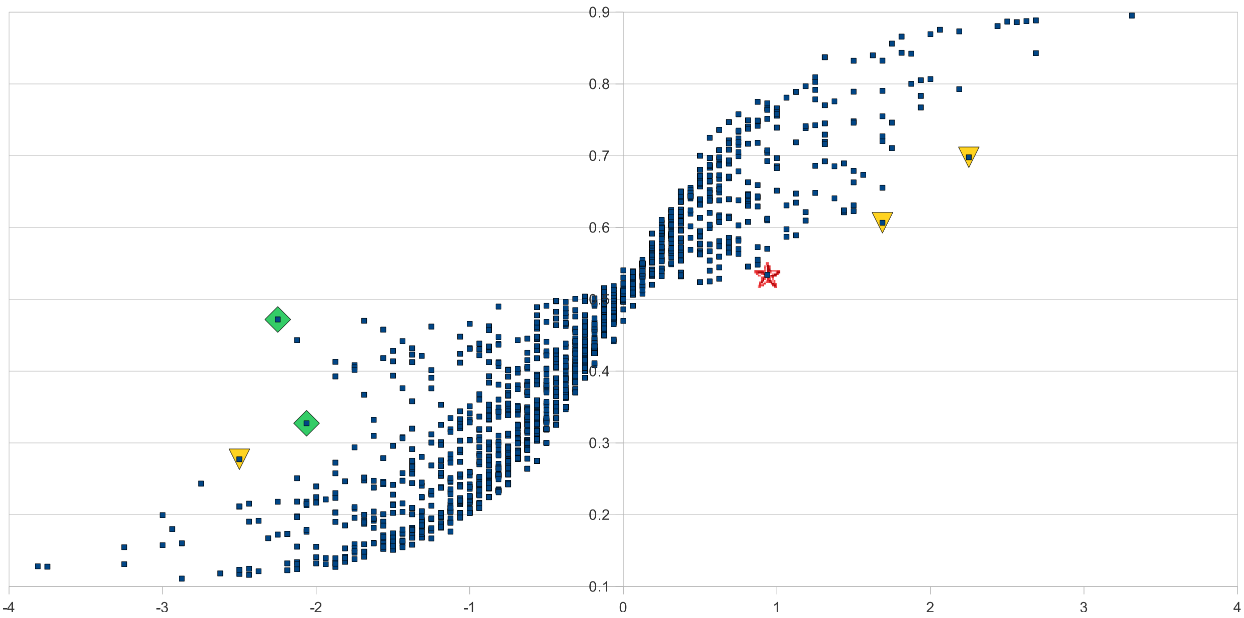

Figure 5: Scatter plot of linear vs probabilistic values

electrical power supply without sacrificing any of the environmental receptors, i.e., none of the receptors could worsen with respect to the original plan. The first query gave a positive result: by producing electricity with environmental friendly power plants (wind-powered aerogenerators) we could produce the same amount of energy but have a 57% improvement on the quality of air.

The second, instead, had a negative result: we could not improve the produced electrical power without worsening at least one receptor. These seemingly contradictory results have actually an interesting explanation. The receptors taken into account by the environmental assessment range on all aspects influenced by a human activity, spanning, e.g., from *value of cultural heritage* to *stability of riverbeds*, from *quality of underground water* to *visual impact on the landscape*. Aerogenerators, recommended in the previous optimization, have a significant visual impact, so they are not implementable unless we relax the visual requirement.

Computing time for this analysis was hardly measurable: all times were far less than a fraction of second on a modern PC. Thanks to such a fast computation, we could comment on-line the results of the queries with the experts of the regional agency, identify errors in the provided data, and try variations of the parameters.

7 Comparison and final choice

Concerning the efficiency, clearly the CLP($\mathcal{R}$) model is significantly faster than the other two, as it uses an efficient solver for linear programming.

Also, this model can be easily extended adding other constraints, in order to solve other types of problems. For example, if the activities were decision variables (instead of fixed values), we could perform automatically the *planning* activity together with the assessment, instead of the assessment alone.

Since the aim of the project is to perform planning together with the assessment, we chose to use the CLP($\mathcal{R}$) approach.

However, we wanted to perform a comparison also on the quality of the results.

In order to have a systematic comparison, we produced two tables (one for each approach) in which each cell contains the effect of single activity on a single receptor. One table reports the results of the CLP($\mathcal{R}$) model and the other those of the causal model. The tables are thus of size $N_a \times N_r = 93 \times 23 = 2139$.

In the scatter plot of Figure 5 we draw the results of the causal model against those of the linear model: the linear model results are on the x-axis, while in the causal model results are on the y-axis. As we can see, most of the points are clustered along a simple curve, which seem to indicate a close relationship between the two models that we are going to investigate in the near future. Moreover, whenever the linear value is positive, the probability of improving the receptor is greater than 0.5 and vice-versa, showing that the two models may disagree on the values, but they agree on the direction of the effect on the receptor.

To better investigate the results, we considered the points farthest from the curve that are highlighted in Figure 5. Since points are those for which the linear and causal model differ the most. We asked the expert to evaluate the results for those points, to understand which model gave the best result. For the points shown as a triangle in Figure 5, the expert was unable to state which answer is better. For the points with a diamond symbol, the CLP($\mathcal{R}$) approach gave a better result. In the point shown as a star, both approaches failed to give a correct result.

From these results, we can say that often the effects can be summed up, although in some cases other combinations could be necessary.

8 Constraint-based model for planning

Given the choice of the model for the environmental assessment as a constraint-based model, we show in this section how we can easily integrate the planning phase using the same modeling abstractions.

To design a constraint-based model for the regional planning activity, we have to define variables, constraints and objectives. Variables represent decisions that have to be taken. We have a vector of activities $\mathbf{A} = (a_1, \ldots, a_{N_a})$. To each activity we associate a variable Mag_i that defines the magnitude of the activity itself. The magnitude could be represented in two ways: in an absolute way as the amount of a given activity or in a relative way, as a percentage with respect of the existing quantity of the same activity. We use in this deliverable the absolute representation.

We distinguish primary from secondary activities: let PA be the set of indexes of primary activities and SA the set of indexes of secondary activities. The distinction is motivated by the fact that some activities are of primary importance in a given plan. Secondary activities are those supporting the primary activities by providing the needed infrastructures. In case of the energy plan, together with environmental and planning experts, we have defined the following distinction. The primary activities that are potentially part of a regional energy plan are those producing energy, namely renewable and non-renewable power plants. Secondary activities are those supporting the energy production, such as activities for energy transportation (e.g., power lines), and infrastructures supporting the primary activities (e.g., dams, yards).

The first set of constraints takes into account dependencies between primary and secondary activities and has the form:

$$\forall j \in SA \quad Mag_j = \sum_{i \in PA} d_{ij} Mag_i$$

Given a budget bud_{Plan} available for a given plan, we have a constraint limiting the overall plan cost as follows

$$\sum_{i=1}^{N_a} Mag_i \, c_i \leq bud_{Plan}$$

This constraint can be posted either on the overall plan, or on parts of it. For instance suppose we have already partitioned the budget into chapters, we can impose the above constraint only on activities related to a given chapter.

Also, given an expected outcome out_{Plan} of the plan we have a constraint ensuring to reach the outcome:

$$\sum_{i=1}^{N_a} Mag_i \, out_i \geq out_{Plan}.$$

For example, in an energy plan the outcome can be to have more energy available in the region, so out_{Plan} could be the increased availability of electrical power (e.g., in megawatts). In such a case, out_i will be the production in MW for each unit of activity a_i.

Concerning objectives, there are a number of possibilities as suggested by planning experts. From an economical perspective, one can decide to minimize the overall cost of the plan (that is anyway subject to budget constraints). Clearly in this case, the most economic energy sources are considered despite their potentially negative environmental effects (which could be anyway constrained). On the other hand, one could maintain a fixed budget and maximize the produced energy. In this case the most efficient energy sources are taken into account. On the other hand, the planner could decide to produce a *green* plan and consider environmental receptors. For example, one can maximize, say, the air quality, or the quality of the surface water. Clearly, the produced plan decisions are less intuitive and in this case the system we propose is particularly useful. The link between decisions on primary and secondary activities and consequences on the environment are extremely complex to be manually considered. The system partitions the budget on activities to obtain a sustainable plan for a given receptor. Clearly, more complex objectives can be pursued, by properly combining the above mentioned aspects. This is subject of current research.

One important aspect to be taken into account when designing a regional energy plan is the energy source diversification: this means that the trend to allocate funds should not be directed toward a single energy source, but should cover both renewable and non renewable energy sources. This requirement comes from fluctuations of the price and availability of the various resources. For this reason, we have posted constraints on the minimal percentage Per_i of the total energy needed to be produced by each energy source i.

$$\forall i \in PA \;\; Mag_i out_i \geq Per_i out_{Plan}$$

In addition, each region has its own geo-physical characteristics. For instance, some regions are particularly windy, while some others are not. Hydroelectric power plants can be built with a very careful consideration of environmental impacts, the most obvious being the flooding of vast areas of land. This poses constraints on the maximum energy Max_i that can be produced by a given energy source i.

$$\forall i \in PA \;\; Mag_i out_i \leq Max_i$$

Finally, the region priorities should be conformant with European guidelines such as the 20-20-20 initiative aimed at achieving three ambitious targets by 2020: reducing by 20% its greenhouse gas emissions, having a 20% share of the final energy consumption produced by renewable sources, and improving by 20% its energy efficiency. For this reason, we can impose constraints on the minimum amount of energy Min_{ren} produced by renewable energy sources whose set is referred to as PA_{ren}. The constraint that we can impose is

$$\sum_{i \in PA_{ren}} Mag_i out_i \geq Min_{ren}$$

Finally, concerning objectives we have that the objective on plan cost minimization is considered as the worst case from an environmental standpoint. On the other hand the best case scenario is the one considering the optimization of one or more environmental receptors.

9 The Regional Energy Plan 2011-2013

The constraint-based model described in previous sections has been used on the planning of the regional energy plan 2011-2013. The system is implemented in the Constraint Logic Programming language ECL^{i}PS^e [1], and in particular uses its Eplex library [27], that interfaces ECL^{i}PS^e with a (mixed-integer) linear programming solver. The computation time is not an issue in this application, and it was hardly measurable on a modern computer.

The regional energy plan had the objective of paving the way to reach the ambitious goal of the 20-20-20 directive, in particular to have 20% of energy in 2020 produced by renewable sources. This 20% does not consider only the electric energy, but the whole energy balance in the region, including thermal energy, and transports.

We concentrate here only on electric energy. The considered electric power plants that produce energy from renewable sources are hydroelectric plants, photovoltaic plants, thermodynamic solar plants, wind generators and, again, biomass power plants.

For each energy source, the plan should provide: the installed power, in MW; the total energy produced in a year, in kTOE (TOE stands for Tonne of Oil Equivalent); the total cost, in M€.

It is worth noting that the considered cost is the total cost of the plant for the regional system, which is not the same as the cost for the taxpayers of the Emilia-Romagna region. In fact, the region can enforce policies in many ways, convincing private stakeholders to invest in power production. This can be done with the financial leverage, or by giving favourable conditions (either economic or other) to investors. Some power sources are economically profitable, so there is no need for the region to give subsidies. For example, currently in Italy biomasses are economically advantageous for investors, so privates are proposing projects to build biomasses plants. On the other hand, biomasses also produce pollutants, they are not always sustainable (see [3] for a discussion) so local committees are rather likely to spawn against the construction of new plants. For these reasons, there is a limit on the number of licenses the region gives for building biomass-based plants. This is subject of future work by integrating the results from WP3 with results from WP4 and WP5.

We used the constraint-based model presented earlier considering initially only "extreme" cases, in which only one type of energy source is used. For instance, if we impose to build only biomass power plants, the application provides in output the spreadsheet file represented in Table 3; the file has the same format as the tables included in the regional energy plan. Beside the plan, the application provides also its environmental assessment, namely an evaluation of the environmental receptors.

Electrical power plants	Power 2010 (MW)	Power 2013 (MW)	Energy 2013 (kTOE)	Investments (M€)
Hydroelectric	300	300	67.06	0
Photovoltaic	230	230	23.73	0
Thermodyn. solar	0	0	0	0
Wind generators	20	20	2.58	0
Biomasses	430	724.47	436.13	1030.64
Total	980	1274.47	529.5	1030.64

Table 3: Example of energy plan for electrical power, if only biomass power plants can be developed

In order to understand the individual contributions of the various energy forms, we plotted all the plans that use a single type of energy in Figure 6, together with the plan developed by the region's experts. On the abscissa, we chose the receptor *Quality of the air* because it is probably the most sensitive in the Emilia-Romagna region. On the y axis we plot the cost of the plan. As explained previously, all plans provide the same energy in

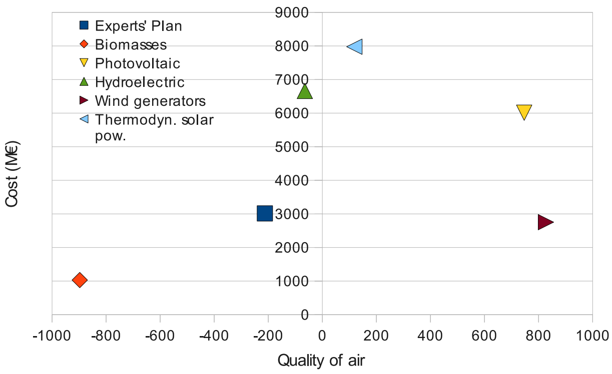

Figure 6: Plot of the *extreme* plans using only one energy source, compared with the plan by the region's experts.

kTOE, while they can require different installation power (in MW).

First of all, we notice that some of the energy types improve the quality of the air (positive values in abscissa), while others worsen it (negative values). Of course, no power plant can improve the quality of the air by itself (as it cannot remove pollutants from the air). The point is that building the plant provides electrical energy without introducing new pollutants; if such energy would not have been provided in the electrical network, it would have been imported from neighbouring regions. In such a case, the required energy would be produced with the same mixture of energy sources as in the national production, including those emitting pollutants, so the net contribution is positive for the quality of the air. Note also that the different energy sources have different impacts on the quality of the air not only due to the emissions of the power plants, but also to the impact of the secondary activities required by the various sources.

Finally, note that the "extreme" plans are usually not feasible, in the sense that the constraint on the real availability of the energy source in the region was relaxed. For example, wind turbines provide a very good air quality at a low cost, but the amount required in the corresponding extreme plan is not possible in the region considering the average availability of wind and of land for installing turbines.

The plan proposed by the region's experts is more *balanced*: it considers the real availability of the energy source in the region, and provides a mixture of all the different renewable types of energy. This is very important in particular for the renewable sources, that are often discontinuous: wind power is only available when the wind is blowing at a sufficient speed, solar power is only available during the day and there is more availability in sunny days, etc., so having a mixture of different sources can provide an energy availability more continuous during the day.

Beside assessing the plan proposed by the experts, we also provided new, alternative plans. In particular, we searched for optimal plans, both with respect to the cost, and to the *quality of the air*. Since we have two objective functions, we plotted the Pareto-optimal frontier; each point of the frontier is a point such that one cannot improve one of the objectives without sacrificing the other. In our case, the quality of the air cannot be improved without raising the cost, and, vice-versa, it is impossible to reduce the cost without sacrificing the quality of the air. The Pareto frontier is shown in Figure 7, together with the experts' plan. Note that being our formulation of the problem linear, we can compute the Pareto frontier by changing coefficients in the objective function that boils down to a weighted sum of single criteria.

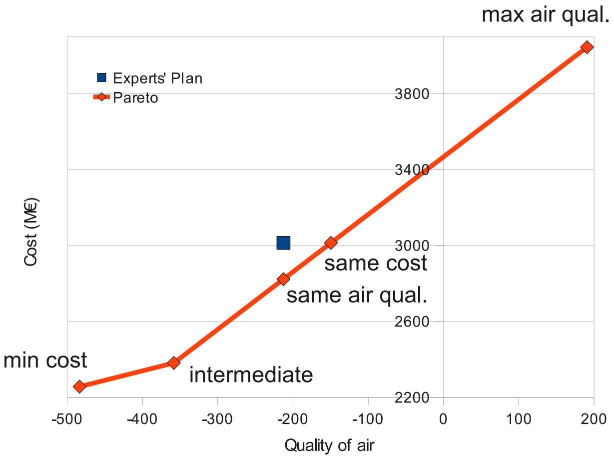

Figure 7: Pareto frontier of the quality of air against cost.

The picture shows that, although the plan devised by the experts is close to the frontier, it can be improved. In particular, we identified on the frontier two solutions that dominate the experts' plan: one has the same cost, but better air quality, while the other has same air quality, but a lower cost.

Electrical power plants	Power 2010 (MW)	Power 2013 (MW)	Energy 2013 (kTOE)	Investments (M€)
Hydroelectric	300	310	69.3	84
Photovoltaic	230	850	87.7	2170
Thermodyn. solar	0	10	1	45
Wind generators	20	80	10.3	120
Biomasses	430	600	361.2	595
Total	980	1850	529.5	3014

Table 4: Energy plan developed by the region's experts

Table 4 contains the plan developed by the region's experts, while Table 5 shows the plan on the Pareto curve that has the same quality of air as the plan of the experts. The energy produced by wind generators is almost doubled (as they provide a very convenient ratio (air quality)/cost, Figure 6), we have a slight increase in the cheap biomass energy, while the other energy sources reduce accordingly.

Concerning the environmental assessment, we plot in Figure 8 the value of the receptors in significant points of the Pareto front. Each bar represents a single environmental receptor for a specific plan plotted in the Pareto Frontier of Figure 7. In this way it is easy to compare how receptors are impacted by different plans. Notice that the receptors

Electrical power plants	Power 2010 (MW)	Power 2013 (MW)	Energy 2013 (kTOE)	Investments (M€)
Hydroelectric	300	303	67.74	25.2
Photovoltaic	230	782.14	80.7	1932.51
Thermodyn. solar	0	5	0.5	22.5
Wind generators	20	140	18.03	240
Biomasses	430	602.23	362.54	602.8
Total	980	1832.37	529.5	2823

Table 5: Energy plan that dominates the experts' plan, retaining same air quality but with lower cost

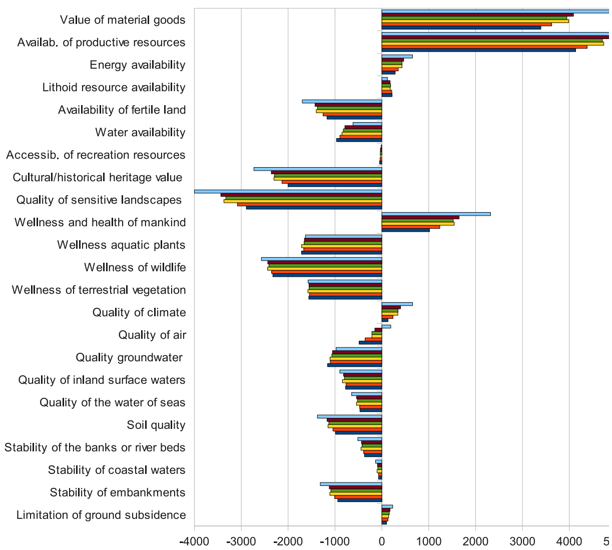

Figure 8: Value of the receptors on the Pareto front

have different trends: some improve as we move towards higher quality of the air (like *quality of climate*, *wellness of mankind*, *value of material goods*), while others improve when moving to less expensive solutions (like *quality of sensitive landscapes*, *wellness of wildlife*, *soil quality*). This is due to several reasons, depending both on the type of power plants installed, and on the secondary activities. For example, wind turbines have a good effect on the quality of the air, but they are also considered aesthetically unpleasant, so they cannot be installed in sensitive zones, like on the hills without having protests from the residents (receptor *quality of sensitive landscapes*). Migratory birds follow wind streams to reduce fatigue in their travel for long distances; on the other hand, wind turbines are to be installed in windy zones to be effective. So, during migration, birds would have a high likelihood to unexpectedly meet large rotating wind blades, possibly impacting with them; this effect cannot be ignored in particular for endangered species (receptor *wellness of wildlife*).

10 Discussion and Open Issues

We have reported the work done in WP3 concerning the model for the global optimizer taking into account the regional perspective on the energy plan. We haev proposed three interpretations of the coaxial matrices for the Strategic Environmental Assessment, one based on a probabilistic meaning of the matrix elements, four models based on fuzzy and multi-valued logic and one based on Constraint Programming. We have chosen the third and we have integrated the planning model in the constraint-based model of the matrices. We have evaluated the model on the data of the Emilia-Romagna regional energy plan 2011-2013 and we have extracted alternative scenarios and the corresponding assessment. The extensive evaluation of the model will be performed in deliverable D3.3 on the version one prototype developed in deliverable D3.2. This prototype will contain also the economic evaluation, while the integration of the simulator will be proposed in deliverable D3.4 and evaluated in D3.5.

References

[1] Krzysztof R. Apt and Mark Wallace. *Constraint logic programming using Eclipse*. Cambridge University Press, 2007.

[2] Paolo Cagnoli. *VAS valutazione ambientale strategica*. Dario Flaccovio, 2010.

[3] Massimiliano Cattafi, Marco Gavanelli, Michela Milano, and Paolo Cagnoli. Sustainable biomass power plant location in the Italian Emilia-Romagna region. *ACM Transactions on Intelligent Systems and Technology*, 2(4):33:11–33:19, July 2011.

[4] Vítor Santos Costa, David Page, Maleeha Qazi, and James Cussens. CLP($\mathcal{BN}$): Constraint logic programming for probabilistic knowledge. In Christopher Meek and Uffe Kjærulff, editors, *UAI '03, Proceedings of the 19th Conference in Uncertainty in Artificial Intelligence, Acapulco, Mexico, August 7-10 2003*, pages 517–524. Morgan Kaufmann, 2003.

[5] Evgeny Dantsin. Probabilistic logic programs and their semantics. In Andrei Voronkov, editor, *Proceedings of the 2nd Russian Conference on Logic Programming*, volume 592 of *Lecture Notes in Computer Science*, pages 152–164, Berlin / Heidelberg, 1991. Springer.

[6] Leslie De Koninck, Tom Schrijvers, and Bart Demoen. INCLP(R) - interval-based nonlinear constraint logic programming over the reals. In Michael Fink, Hans Tompits, and Stefan Woltran, editors, *WLP*, volume 1843-06-02 of *INFSYS Research Report*, pages 91–100. Technische Universität Wien, Austria, 2006.

[7] Luc De Raedt, Angelika Kimmig, and Hannu Toivonen. ProbLog: A probabilistic Prolog and its application in link discovery. In Manuela M. Veloso, editor, *IJCAI 2007, Proceedings of the 20th International Joint Conference on Artificial Intelligence, Hyderabad, India, January 6-12, 2007*, pages 2462–2467, 2007.

[8] D. Dubois and H. Prade. *Fuzzy Sets and Systems: Theory and Applications*. Academic Press, 1980.

[9] Didier Dubois and Henri Prade. Possibility theory, probability theory and multiple-valued logics: a clarification. *Annals of Mathematics and Artificial Intelligence*, 32(1-4):35–66, 2001.

[10] Norbert Fuhr. Probabilistic Datalog: Implementing logical information retrieval for advanced applications. *Journal of the American Society for Information Science*, 51(2):95–110, 2000.

[11] Marco Gavanelli, Fabrizio Riguzzi, Michela Milano, and Paolo Cagnoli. Logic-Based Decision Support for Strategic Environmental Assessment. *Theory and Practice of Logic Programming, 26th Int'l. Conference on Logic Programming (ICLP'10) Special Issue*, 10(4-6):643–658, July 2010.

[12] Petr Hájek. *Metamathematics of Fuzzy Logic (Trends in Logic)*. Springer, 1 edition, November 2001.

[13] Manuel V. Hermenegildo, Francisco Bueno, Manuel Carro, Pedro López-García, José F. Morales, and Germán Puebla. An overview of the Ciao multiparadigm language and program development environment and its design philosophy. In Pierpaolo Degano, Rocco De Nicola, and José Meseguer, editors, *Concurrency, Graphs and Models*, volume 5065 of *Lecture Notes in Computer Science*, pages 209–237, Berlin/Heidelberg, 2008. Springer.

[14] Joxan Jaffar and Michael J. Maher. Constraint logic programming: A survey. *Journal of Logic Programming*, 19/20:503–581, 1994.

[15] Joxan Jaffar, Spiro Michaylov, Peter J. Stuckey, and Roland H. C. Yap. The CLP($\mathcal{R}$) language and system. *ACM Transactions on Programming Languages and Systems*, 14(3):339–395, 1992.

[16] W. Meert, J. Struyf, and H. Blockeel. CP-Logic theory inference with contextual variable elimination and comparison to BDD based inference methods. In L. De Raedt, editor, *Proceedings of the 19th International Conference on Inductive Logic Programming*, Leuven, Belgium, 2009. KU Leuven.

[17] Vilém Novák. Mathematical fuzzy logic in narrow and broader sense - a unified concept. In Masoud Nikravesh and Mo Jamshidi, editors, *BISCSE'05*, University of California-Berkeley, November 2005. The Berkeley Initiative in Soft Computing.

[18] J. Pearl. *Causality*. Cambridge University Press, 2000.

[19] David Poole. The independent choice logic for modelling multiple agents under uncertainty. *Artificial Intelligence*, 94(1-2):7–56, 1997.

[20] Regione Emilia-Romagna. Il secondo piano triennale di attuazione del piano energetico regionale 2011-2013, July 2011. http://bur.regione.emilia-romagna.it/dettaglio-inserzione?i=f1fc8c3c7f211ad02579c95ad8dc317a.

[21] Fabrizio Riguzzi. A top down interpreter for LPAD and CP-logic. In R. Basili and M. T. Pazienza, editors, *AI*IA 2007: Artificial Intelligence and Human-Oriented Computing*, volume 4733 of *Lecture Notes in Artificial Intelligence*, pages 109–120, Berlin/Heidelberg, 2007. Springer-Verlag.

[22] Fabrizio Riguzzi. Inference with logic programs with annotated disjunctions under the well founded semantics. In Maria Garcia de la Banda and Enrico Pontelli, editors, *Logic Programming, 24th International Conference, ICLP 2008, Udine, Italy, December 9-13 2008, Proceedings*, volume 5366 of *Lecture Notes in Computer Science*, pages 667–671. Springer, 2008.

[23] Fabrizio Riguzzi. Extended semantics and inference for the Independent Choice Logic. *Logic Journal of the IGPL*, 17(6):589–629, 2009.

[24] J.J. Saade. A unifying approach to defuzzification and comparison of the outputs of fuzzy controllers. *Fuzzy Systems, IEEE Transactions on*, 4(3):227–237, Aug 1996.

[25] Taisuke Sato and Yoshitaka Kameya. PRISM: A language for symbolic-statistical modeling. In Martha E. Pollack, editor, *International Joint Conference on Artificial Intelligence*, pages 1330–1339. Morgan Kaufmann, 1997.

[26] Joachim Schimpf and Kish Shen. ECL^{i}PS^{e} - from LP to CLP. *Theory and Practice of Logic Programming*, 12(1-2):127–156, 2012.

[27] Kish Shen and Joachim Schimpf. Eplex: Harnessing mathematical programming solvers for constraint logic programming. In P. van Beek, editor, *Principles and Practice of Constraint Programming - CP 2005*, volume 3709 of *Lecture Notes in Computer Science*, pages 622–636, Berlin/Heidelberg, 2005. Springer-Verlag.

[28] Jens C. Sorensen and Mitchell L. Moss. Procedures and programs to assist in the impact statement process. Technical report, Univ. of California, Berkely, 1973.

[29] Allen Van Gelder, Kenneth A. Ross, and John S. Schlipf. The well-founded semantics for general logic programs. *J. ACM*, 38(3):620–650, 1991.

[30] J. Vennekens, S. Verbaeten, and M. Bruynooghe. Logic programs with annotated disjunctions. In Bart Demoen and Vladimir Lifschitz, editors, *International Conference on Logic Programming*, volume 3131 of *Lecture Notes in Computer Science*, pages 195–209, Heidelberg, Germany, 2004. Springer.

[31] Joost Vennekens, Marc Denecker, and Maurice Bruynooghe. CP-logic: A language of causal probabilistic events and its relation to logic programming. *Theory and Practice of Logic Programming*, 9(3):245–308, 2009.

[32] Nikolaus Wulff and Davide Sottara. Fuzzy reasoning with a Rete-OO rule engine. In Guido Governatori, John Hall, and Adrian Paschke, editors, *RuleML*, volume 5858 of *Lecture Notes in Computer Science*, pages 337–344. Springer, 2009.

[33] Lotfi A. Zadeh. Fuzzy sets. *Information and Control*, 8(3):338–353, 1965.

[34] Neng-Fa Zhou, Isao Nagasawa, Masanobu Umeda, Keiichi Katamine, and Toyohiko Hirota. B-Prolog: A high performance Prolog compiler. In Takushi Tanaka, Setsuo Ohsuga, and Moonis Ali, editors, *IEA/AIE*, page 790. Gordon and Breach Science Publishers, 1996.