Compromise Seeking for Power Line Path Selection Based on Economic and Environmental Corridors

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***Abstract*--This paper presents a new multi-criteria Decision Aid System (DAS) to obtain acceptable power line paths integrating the diverse socio-economic interests of the different Groups involved in the planning process, such as utilities, environmental agents or local and regional authorities. The DAS is based on the intensive use of Geographic Information Systems (GIS), as well as multi-criteria weighting techniques reflecting all Group interests. This new DAS can be used to overcome the problems raised by initially opposing positions among different Groups stemming from diverse technological, economic, environmental and/or social interests. The technique is illustrated by an intensive simulation example from a case study reproducing some of the phases of a negotiation process.**

***Index Terms*--Decision support system, decision-making, geographic information systems, optimization methods, power systems**

I. Introduction

THE construction of new power infrastructures (electric power lines or gas pipelines) constitutes a technical, economic and social problem. Agreement on the selection of the definite path for a new line is subject to the often conflicting interests of the different Groups involved. For instance, utilities will aim at power lines that are more attractive in economic terms. For other agents, such as environmentalists or local authorities, the construction of new lines crossing certain locations might have an unacceptable impact. This conflict of interests can delay and even obstruct the construction of new power lines.

This paper presents a new multi-criteria Decision Aid System (DAS) to find a set of the best efficient line paths as a compromise among the objectives of two Groups: an "economic interest Group" (that may represent electric utilities, investors or other economic agents seeking the lowest cost path); and an "environmental interest Group" (that may stand for social organizations, local authorities or other entities with environmental interests, pushing for a path with the lowest value of cumulative impact indexes, based on environmental criteria). Solving this problem involves several aspects: a) the use of Geographic Information Systems (GIS) to integrate geographic realities of the problem; b) the use of GIS spatial optimization to find the best line paths; and c) the use of a multi-criteria approach to reach compromises among the environmental and economic interests of the Groups.

Recently the use of GIS has become commonplace in several leading professional automation planning distribution software packages, due to their ability to deal with the geographic realism of the problem, offering new interface capabilities to planners. Most applications are related to distribution planning, starting by locating loads with spatial load forecasting [1] and [2], load analysis for transformer load management [3], underground cable routing for urban distribution [4], distribution feeder optimization using spatial dynamic programming [5] and [6], automation of distribution planning including substation sitting optimization [7], and general line routing based on path corridor optimization [8].

The environmental factors were typically proposed for inclusion in the power systems planning process as optimization constraints [9]. Only a few models have included environmental criteria in line routing optimization [10], but using solely information from experts in the first stages of the planning process for a prior evaluation of the probability of the proposed route being accepted by Groups and in order to study exclusively projects with high possibility of acceptance.

Multi-Criteria Decision Aid (MCDA) systems have been proposed in different approaches as renewable energy planning tools [11], and for geographical location of disperse generation [12]. The authors have previously proposed [13] an original GIS-based Negotiation Aid System (NAS) for a negotiation process among Groups to select locations for the construction of new wind parks. Negotiation was supervised by the NAS, helping in the selection of weights for Group criteria by using a geographic interface. In this paper, such methodology is adapted and applied specifically for the selection of weights of the environmental Group criteria to obtain an environmental attribute map that reflects the group preferences.

Only one reference [14] deals with GIS corridor optimization and multi-criteria approaches applied to linear

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infrastructures; it uses an economic path optimization to obtain starting solutions and extracts values for environmental criteria in these paths using GIS. The compromise solution between environmental and economic interests is found by performing a posteriori analysis based on ELECTRE III [15], a MCDA technique. Since the routing optimization and the multi-criteria approach are performed in separate stages, the methodology helps to select among a set of good economical paths, but does not directly find the entire range of efficient optimal paths, as we achieve with our approach.

For the project of a new line between two geographical points (origin and destination of the new power line), the DAS described in this paper helps in defining:

- line corridors preferred by an environmental Group and an economic Group (corridors are elongated areas defined by geographical bounds that include optimum and near optimum paths for the objectives of the groups);
- multi-criteria efficient corridors (non-dominated paths in terms of Pareto optimality) that can not be better simultaneously in the objectives of both groups.

Thus, the DAS leads to a limited number of efficient paths avoiding the evaluation of a huge number of possible paths between the two geographical points. The negotiation process between the two groups becomes facilitated since they only need to concentrate on a few efficient paths to select the most acceptable one for the new line installation. It is important to understand the difference between a Decision Aid System and a Negotiation Aid System (NAS). In a DAS, one admits being in the presence of a single decision maker (DM) who has to conciliate several objectives of his own. A NAS, instead, assumes a number of independent actors that may not share the same points of view or even the same criteria in evaluating solutions for a problem. The strategy followed in this paper is to facilitate a negotiation between different actors by defining aggregate measures to classify solutions for each actor, in order to reduce the problem to the search for a compromise by a "meta-DM". This is why we refer to the technique as a DAS, although we are in fact modeling a negotiation process.

II. Problem, Objectives And Nomenclature

We consider two interest Groups with different profiles: an economic interest Group (*Eco*) and an environmental interest Group (*Env*) of Decision Makers. The objective of the *Eco* is to find the lowest cost paths for a power line to be built between two geographical points, based on monetary criteria. The objective of the *Env* is to find paths with the lowest value of cumulative impact indexes, based on environmental criteria. Both groups are interested in selecting a path between two geographical points (origin and destination) but they do not coincide on the geographical areas to be routed by the path.

For the DAS (Decision Aid System) studied in this paper, the problem consists in identifying path alternatives E, which cannot be improved simultaneously in the objectives of both interest Groups (efficient or non-dominated in terms of Pareto optimality). Such efficient path alternatives represent highly valuable information for both groups that, during the following negotiation process, will be asked to select possibly one of those alternatives as the definite path for building the new line.

The criterion map $C_{c,n}$ is a geographical information coverage in a GIS used to define a preference guideline for criterion c of Group n. For the *Env*, the criteria maps could be terrain usage, geographical patterns for specific local or regional environmental interest, historical and cultural classification, distance to geographical features, etc. For the *Eco*, the main criteria are the geographical coverages that influence the total economic cost of the line, such as terrain cost, accessibility for installation, maintenance and repair, terrain slope, etc. Each Group n independently adopts its own set of Criteria c.

An attribute map $T_{c,n}$ is a map with a measurement of Group n of each spatial feature, in criterion c, for the standpoint of this Group. In our approach, attributes are defined by internal value functions established by each Group n. The attribute map T is a map reclassification value over each criterion map C. The *Env* uses, for attribute map $T_{c,Env}$, a non-monetary attribute scale between 1, for very bad locations, and 0, for acceptable locations. Such $T_{c,Env}$ has to be transformed to a standardized attribute map $T'_{c,Env}$ (described in section III). The *Eco* uses a monetary attribute scale for attribute map $T_{c,Eco}$. The geographical locations totally intolerable for at least one of the Groups are filtered at the beginning of the process.

Based on criteria weights $CW_{c,n}$, the aggregation of the attribute maps for the several criteria c of each Group n results in an aggregated attribute map T_n. For the *Env* , which uses the non-monetary attribute scale, the weights $CW_{c,Env}$ are defined by the *Env DMs* with the supervision of the DAS. For the *Eco*, which uses a monetary attribute scale, the weights $CW_{c,Eco}$ are automatically defined as 1.

The partial group corridor map R_n is the "line corridor" from the point of view of the interest Group n. The partial group corridor map R_n is obtained using a "minimum cost" path optimization algorithm, running over the geographical aggregated attribute map T_n. A scale transformation is applied to R_n to fit in a new scale between 0 (optimal path of the Group) and 1 (outer corridor bound corresponding to maximum "cost" threshold [8] for the Group) resulting in the standardized partial Group corridor map R'_n.

The map of the global utility function $F_{GWEco,GWEnv}$ represents a map with weighting values of R'_{Eco} and R'_{Env} for group weights GW_{Eco} and GW_{Env} used to find the efficient path alternatives $E_{GWEco,GWEnv}$. Note that the Group weights (GW_{Eco} and GW_{Env}) are not related to the criterion weights ($CW_{c,Eco}$ and $CW_{c,Env}$). The Group weights are values between 0 (lowest Group weight in the global utility function of the line paths) and 1 (highest Group weight) used successively by the DAS to find the set of efficient path alternatives.

III. Methodology

The methodology applied in this paper follows the sequential procedure shown in the diagram in Fig. 1. The procedure is divided in two different stages. The first stage computes, in independent processes, the set of preferred path alternatives or standardized partial Group corridor map R'_n for each interest Group - in our case, for *Eco* (block A) and *Env* (block B). In the second stage, the efficient path alternatives $E_{GWEco,GWEnv}$ are identified (block C).

In the first stage of the procedure, two types of decision problems may appear. The simplest situation occurs when all the criteria have monetary attributes. This is the case of the *Eco*: all the attribute maps can be aggregated in a unique cost map T_{Eco}. A more complex situation arises when several non-monetary criteria (c) exist, such as for the *Env*. In this case, multi-criteria approaches must be used. The DAS plays the role of a meta-DM or supervisor, by the use of geographical interfacing with the Group, the selection of criteria maps $C_{c,Env}$, the definition of attribute maps $T'_{c,Env}$, the definition of criteria weights $CW_{c,Env}$, and the aggregation of criteria in a unique attribute map T_{Env} representing the preferences of the Group.

Standardization is necessary in certain steps in order to define and apply the weighting calculations without the influence of the initial scaling. A standardization process consists in a linear adjustment of a value V on the initial scale, between the minimum V_{min} and the maximum V_{max}, to a new value V' on a new scale between 0 (maximum preference) and 1 (minimum preference). Then for any map standardization is applied the simple scale transformation represented by $V' = (V - V_{min})/(V_{max} - V_{min})$.

An important aspect is that the aggregation of the preferences of several Groups is not the aggregation of area attribute maps but the aggregation of line path alternatives. To solve this problem, we used the concept of standardized partial Group corridors maps (maps R'_{Env} and R'_{Eco}). As indicated in Section II, the standardized partial Group corridors are elongated areas including the optimal path (represented by 0) of the Group and others near the optimal path and the worst path (but acceptable to the Group) in the corridor that corresponds to the outer bound (with value 1) of the corridor. Each location or cell inside the corridor has an associated a value, between 0 and 1, that represents the degree of utility value deviation from the optimum path of the Group. Because the partial corridor of each Group may have a geographical overlapping with the other Group corridor, efficient path alternatives can be found by the DAS allowing certain geographical relaxation from the optimal path of each Group.

The DAS finds efficient path alternatives $E_{GWEco,GWEnv}$ to be considered for a final decision to be taken on the path of the line to be built. A least-cost path algorithm finds the optimal path between two geographical points, using the map of the following global utility function $F_{GWEco,GWEnv}$:

$$F_{GWEco,GWEnv} = GW_{Env} \cdot R'_{Env} + GW_{Eco} \cdot R'_{Eco} \qquad (1)$$

The global utility function $F_{GWEco,GWEnv}$ represents, for each map cell, the value of a linear-weighted aggregation (by Group weights GW_{Eco} and GW_{Env}) of the distances to the optimal path for each Group (standardized partial Group corridor maps R'_{Eco} and R'_{Env}). The optimal path of the global utility function $F_{GWEco,GWEnv}$ corresponds to the path with the minimum weighted distance to the two optimal paths of the two Groups (not a geographical distance but a “distance” in the space of path alternatives). Thus, this solution of $F_{GWEco,GWEnv}$ for given weights GW_{Eco} and GW_{Env} cannot be improved simultaneously in the objectives of any of both Groups. Different combinations of weights GW_{Eco} and GW_{Env} yield different efficient paths. The Pareto-optimal border is thus discovered (assuming that it is convex, an usual assumption).

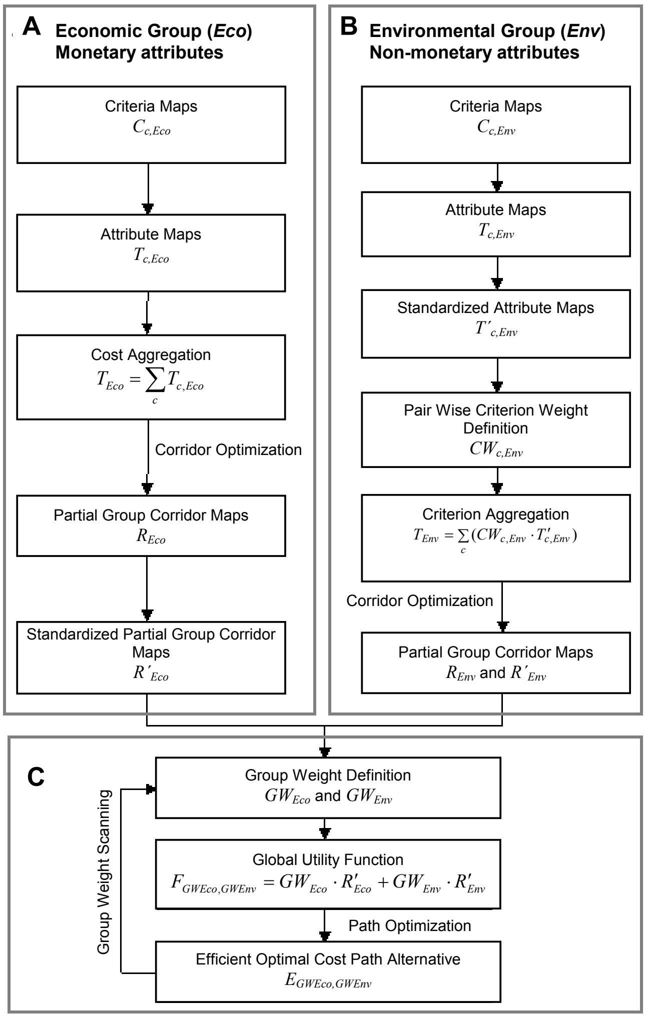

Fig.1. Procedure for the DAS.

A. Path Corridor for the Economic interest Group

The criteria $C_{c,Eco}$ are represented by maps of GIS raster structures (grids). These are regular matrices of square cells, each representing an elementary geographical area (in two dimensions) with homogeneous characteristics. Using this structure, the raster routing algorithms of usual GIS platforms are based on matrix operations, where a matrix corresponds to a GIS coverage (of terrain costs, terrain slope, soil types, or coverage of other aspects) and the information in each matrix element corresponds to alphanumerical information associated with the corresponding geographical location (economic cost for traversing the location with a power line, average slope surrounding the location that influences the power line building cost, etc.).

For *Eco,* all the attribute maps $T_{c,Eco}$ for criteria *c* are based on monetary attributes. Thus, these maps could be lumped up in a single aggregate attribute map T_{Eco} by directly summing the maps $T_{c,Eco}$. The attribute maps $T_{c,Eco}$ are maps with elementary geographical costs, for each cell, representing the costs of traversing the elementary portion of terrain represented by this cell. The approach followed here has been described in detail in [8].

For new overhead lines, in applications with a relatively low GIS resolution (e.g. square cell area of 0.5x0.5 km), the costs of sections of overhead lines (including overhead conductors, insulators and towers) are assumed to be uniformly distributed along the line path (with a cost per km). For path routing, these terrain-distributed costs are also a suitable economic representation in higher resolutions.

Some economic costs ("non-geographical costs") associated with the electric power line are not geographically dependent (cost per km of the line equipment); however, their inclusion in the path routing process is important because their relative value in the overall installed line cost influences the line path optimization carried out by raster routing algorithms in GIS platforms. If these non-geographical costs are important in relation to the geographical cost components, then the path selection will be less sensitive to the geographical characteristics and, therefore, it will result in a straighter path. These non-geographical costs, like line equipment, should be included in the raster GIS coverage as attributes $T_{c,Eco}$ that represent monetary criteria $C_{c,Eco}$. The attribute coverages must represent several economic cost components, as a function of the geographical variables affecting the elementary cell cost for the power line project (line installation, operation and maintenance). These variables influence the costs associated with the equipment to be installed in each location, terrain usage and complexity, indemnities, transposition of obstacles, project considerations relating to meteorological severity at the location, special additional costs associated with environmental and social requirements, etc. The aggregated attribute map T_{Eco} is the sum of several components (attribute maps $T_{c,Eco}$) of empirical cost functions.

The approach used for cost optimization employs geospatial Dynamic Programming (DP) optimization [8]. The DP optimization algorithm finds the minimum (optimal) accumulated cost path between a source point (cell) *A* and each of the cells in the geographical coverage, by moving successively from neighboring cells (using the Bellman principle of optimality) and storing an optimal "back-link cell path" from each cell of the coverage to point *A*; these "back-link cell paths" form a "radial structure" from *A*. The transition between neighboring cells is carried out using the elementary cell costs stored in the aggregated attribute map T_{Eco}.

The computation of the corridor for *Eco* (partial Group corridor map), say between two geographical points *A* and *B* involves the following:

- the DP optimization algorithm determines the optimal path from the source point *A* to each cell of the geographical coverage, resulting in an accumulated economic cost coverage $G_{Eco,A}$;
- the DP algorithm finds the optimal cost paths from source point *B* to all the cells of the coverage, obtaining an accumulated cost coverage $G_{Eco,B}$;
- the cost of the optimal path between the points *A* and *B* passing throughout a generic third geographical point *D* is computed and stored (in cell *D*) by adding the accumulated cost coverages $G_{Eco,A}$ and $G_{Eco,B}$, i.e. adding the cost values of $G_{Eco,A}(D)$ and $G_{Eco,B}(D)$ in each cell *D* of the resulting coverage J_{Eco} to obtain the corresponding value $J_{Eco}(D)$.

Thus, for each geographical point D:

$$J_{Eco}(D) = G_{Eco,A}(D) + G_{Eco,B}(D) \tag{2}$$

Thus, J_{Eco} is a coverage that stores, in each cell *D* corresponding to the geographical point D, the cost associated with the optimal path (between the geographical points *A* and *B*) that crosses this geographical point *D*. The set of cells with the minimum cost value in coverage J_{Eco} corresponds to the optimal path between points *A* and *B* (of optimal cost for power line installation). A set of other cells, with a given slightly higher cost value (above the minimum cost value in J_{Eco}) corresponds to a near optimal path. A predefined value h_{max} (above the minimum cost value in J_{Eco}) for the acceptable maximum cost of the power line installation determines the set of cells constituting the outer geographical bound of coverage J_{Eco}. Such bounded coverage is the corridor R_{Eco} for *Eco* (partial Group corridor map).

By applying the abovementioned standardization to economical corridor map R_{Eco}, the standardized economic corridor map R'_{Eco} is obtained. This last corridor map is a coverage with value 0 for the optimal economic path (the best path from an economic standpoint) and value 1 for the worst economic (but economically acceptable) path corresponding to the outer corridor bound. Note that for a given geographical point *D*, its value in R'_{Eco} represents a "distance" value from the least-cost path (between points *A* and *B*) passing through *D* to the optimal economic path of R'_{Eco} (not a geographical distance but a "distance" in the space of path alternatives).

B. Path Corridor for the Environmental interest Group

For *Env*, block B in Fig. 1 indicates the steps for computing its line path corridor. The role of the DAS is to help *Env* to define its own preferences and clarify the relative importance of the variables involved. This requires an innovative DAS approach using GIS techniques based on previous research by the authors [13], summarized in the following paragraphs.

The criteria maps $C_{c,Env}$ are selected by *Env* from a set of geographical maps. Examples of criteria are: actual legal environmental restrictions, distances to inhabited areas, animal protected areas, distance to historical monuments, visual impact index, etc. An attribute map $T_{c,Env}$ is a map with a measure of *Env* preference relative to each spatial feature, in criterion *c*. The DAS transforms this attribute map ($T_{c,Env}$) into a standardized map $T'_{c,Env}$ valued from 0 to 1 - most preferred to least tolerable locations.

The pair-wise weight definition consists in assisting *Env* in defining the criteria weights $CW_{c,Env}$. For each pair of criteria *p* and *q*, *Env* determines the best values of pairs of "relative criteria weights" by choosing the aggregate map with a spatial pattern that is most coherent with its preferences and tolerances [13]. For each pair of criteria *p* and *q*, the DAS builds the aggregation function $S_{p,q} = (z_p \cdot T'_{p,Env}) + (z_q \cdot T'_{q,Env})$ for a series of weights (z_p, $z_q = 1 - z_p$, where z_p = 0, 0.1, …. 0.9, 1), and constructs the corresponding map $S_{p,q}$. *Env* selects ($z_{p,select}$, $z_{q,select}$) from the fittest aggregated attribute map of the criteria *p* and *q*, with its own preferences and tolerances.

Fig. 2, 3 and 4 show examples of three maps of the aggregation function $S_{p,q}$ corresponding to three pairs of weight values for two illustrative criteria, namely "Distance to Roads" $T'_{DR,Env}$ and "Distance to Inhabited areas" $T'_{DI,Env}$. These maps were built from data referring to the region of La Rioja in Spain. The $T'_{DR,Env}$ attribute represents the environmental preference to see power lines close to the roads in order to concentrate the impact of roads and power lines in the same geographical areas. The $T'_{DI,Env}$ reflects a similar effect, i.e., the preference to concentrate the impact of overhead power lines near suburban areas but not too close to urban center cores. In Fig. 2 the weight value (0.8) for distance to inhabited areas is considerably higher than the weight value (0.2) for distance to roads. Note that areas near urban center cores ("urban centers" in Fig. 2) display lower tolerance to power line traversal (darker regions outside the "urban centers"). For this combination of weights the importance of the distance to roads is insufficient (from *Env* standpoint), requiring changes in the selection of weight values. In Fig. 3 the weights change, placing greater importance on distance to roads. Passing through urban centers was not sufficiently penalized; consequently, this weight combination was found also inadequate. The most adequate combination of weight values can be found by a suitable interaction between the *Env* and the DAS, using a systematic successive bisection process. For this example, the *Env* found the pair-wise weight values z_{DR}=0.4 and z_{DI}=0.6 as an adequate definite set (Fig. 4). Based on the ($z_{p,select}$, $z_{q,select}$) relative weights between pairs of criteria, it is possible to identify the corresponding "global relative weights" $CW_{c,Env}$ for all *c* criteria so that *Env* preferences are not dependent on scaling or subjective appreciation of criteria. To achieve this, let us define the classic Saaty matrix [16] by elements $a_{pq} = (z_{p,select} / z_{q,select})$. Using Chu's method [17], the global relative weights $CW_{c,Env}$ are obtained by solving the following simple optimization problem (where $CW_{c,Env}$ are the optimization variables):

$$\begin{aligned} &Min \quad \sum_p \sum_q \left(a_{pq} \cdot CW_{q,Env} - CW_{p,Env} \right)^2 \\ &s.t. \quad \sum_p CW_{p,Env} = 1 \quad ; \quad 0 \le CW_{p,Env} \le 1 \end{aligned} \tag{3}$$

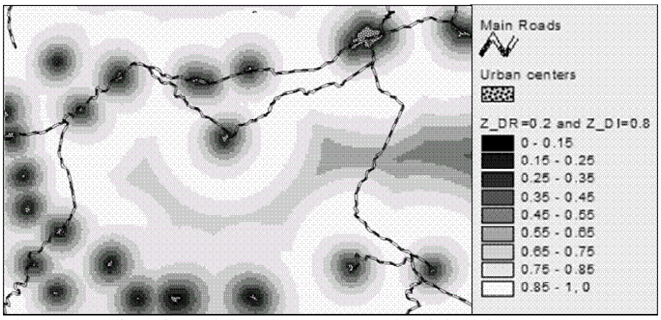

Fig. 2. Map of $S_{p,q}$ for weight value z_{DR}=0.2 and weight value z_{DI}=0.8

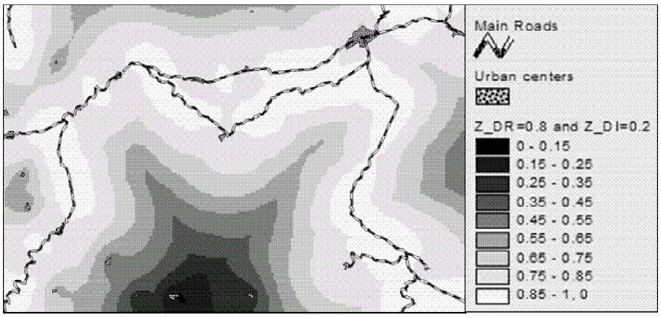

Fig. 3. Map of $S_{p,q}$ for weight value z_{DR}=0.8 and weight value z_{DI}=0.2

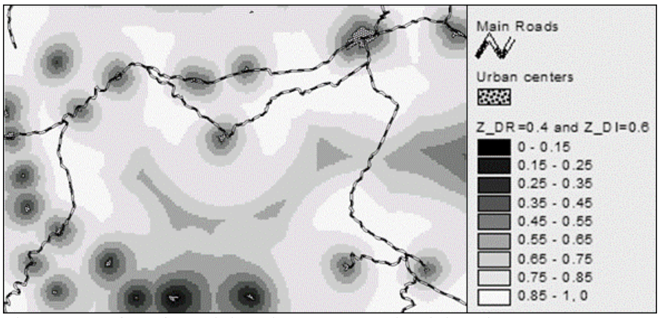

Fig. 4. Map of $S_{p,q}$ for weight value z_{DR}=0.4 and weight value z_{DI}=0.6

The aggregated attributed map T_{Env} is obtained from the attributes $T'_{c,Env}$, as follows:

$$T_{Env} = \sum_c (CW_{c,Env} \cdot T'_{c,Env}) \tag{4}$$

The result is a single map of aggregated preference/tolerance attributes of the *Env*, with T_{Env} values between 0 (environmentally best locations for power lines installations) and 1 (environmentally worst locations, but still acceptable for line installations) associated to each map cell. Like for the economic corridors, the DP optimization algorithm is applied over T_{Env}, with the same source and end point locations (*A*, *B*), and an accumulated environmental impact index (J_{Env}) associated to the optimal path (the set of cells connecting *A* and *B* with the minimum accumulated impact index) is built. The environmental corridor R_{Env} is the coverage J_{Env} limited by the maximum allowed environmental impact index defined by *Env*.

The final DAS step, for non-monetary criteria, consists in the computation of the line path corridor (standardized partial corridor map R'_{Env}) of the *Env* - a coverage with value 0 for the optimal line path and value 1 for the environmentally least-tolerable line paths corresponding to the outer corridor bound. Note that, for a given point *D*, its value in R'_{Env} represents a value of aggregate attribute distance from the environmental least-impact path (between points *A* and *B*) passing through *D* to the optimal path of R'_{Env}.

C. Efficient path compromises for power line installation

Block C in Fig. 1 corresponds to determine efficient compromise paths by applying the DP optimization algorithm to the global utility function $F_{GWEco,GWEnv}$ defined in (1).

Group weights GW_{Eco} and GW_{Env}=(1-GW_{Eco}) are generated systematically using a pre-defined discrete step. For a given pair of weights GW_{Eco} and GW_{Env}, the efficient path has a minimum weighted "attribute distance" to the two optimal paths (in R'_{Eco} and R'_{Env}) of the two Groups.

A smaller step corresponds to a more detailed and broader search of the efficient path alternatives. For example, a step of 0.1 produces eleven different weights combinations (with GW_{Eco} values of 0, 0.1, 0.2, … , 0.8, 0.9 and 1), from GW_{Env}=1 and GW_{Eco}=0, corresponding to an efficient path alternative with absolute preference for the *Env*, to GW_{Eco}=1 and GW_{Env}=0, corresponding to an efficient path alternative with absolute preference for the *Eco*. In order to generate alternative scenarios without absolute preference for any of the groups, the hypothetical weights with value 0 and 1 are changed to 0.001 and 0.999, respectively.

IV. Case Study

This section presents the results of a case study in a selected region of La Rioja (Spain). The problem consisted in identifying efficient path alternatives for a 66 kV overhead power line installation with an ACSR-350 conductor size, bearing in mind that the decision regarding the best path for such line installation involved two interest groups: the *Env* and the *Eco*. Each group was represented by one of its Decision Makers, who interacted with the Decision Aid System to select the criteria and set the geographical attributes and the weights of each criterion. As a result, the DAS provided a set of efficient path alternatives for the problem, the values of the map R'_n of the path alternatives acceptable for each Group, and other attributes associated with each path.

A. Path Corridor for the Economic interest Group

By applying the steps of block A in Fig. 1, the economic costs of T_{Eco} are given (in Euros/m or €/m; GIS resolution of 100x100m) in Fig. 5. This map also shows the location of the source (A,■) and the destination (B,▲). The aggregate attribute map T_{Eco} is the result of the aggregation of several cost components for different monetary attribute criteria involved in (5).

$$T_{Eco} = C_{equipment} + C_{terrain} + C_{instalation} + C_{weather} + C_{environment\_safety} \quad (5)$$

In (5) all the costs components (in €/m) were a linear function of the length of the line. The criteria and typical cost components included in (5) were:

- $C_{equipment}$: the cost of the equipment that was not dependent on geography.
- $C_{terrain}$: the cost of terrain dependent on terrain usage and reference prices fixed by municipalities.
- $C_{instalation}$: a component associated with additional costs caused by extra difficulties: accessibility (distance to roads), clearing of vegetation, terrain slopes and other complexities in terms of orography, rocky soils, etc. This cost was geographically dependent on multiple GIS coverages and it was attributed a monetary additional cost that changed geographically (according to the characteristics of each location).
- $C_{weather}$: a component associated with an additional cost caused by reinforcements in the equipment to support adverse weather conditions. The geographical criteria coverages used to map these additional costs were snow region, windy region and lightning frequency maps.
- $C_{environment\_safety}$: a cost component showing the additional cost needed to compensate special requirements due to the crossing of protected environmental areas or populated areas that demand safety procedures.

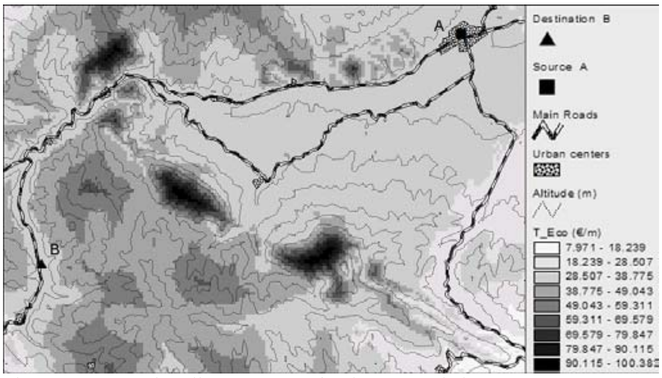

Fig. 5. Aggregated attribute map T_{Eco} for the economic interest Group.

Fig. 5 shows the geographical pattern of the aggregate attribute map for the *Eco* preferences, resulting from the overall component cost aggregation of (5). The darker regions correspond to higher cost influenced by the complexity of the orography and by the distance to primary roads; the effects of the other geographical factors are embedded in the complexity resulting from the cost components aggregation.

By applying the DP optimization algorithm of section III and following the steps in block A of Fig. 1, the line corridor R_{Eco} was computed. Fig. 6 presents isolines of costs (in €) of J_{Eco} showing that good paths did not necessarily follow contiguous areas. For instance, the optimal economical path, mapped as a geographical white raster line, had an economical cost of 611895 €, but another possible path in the NW of the mountain also had good economic value of 615550 €. The selected maximal acceptable economical cost was h_{max}=72000 €, which defines the upper bound of economical corridor R_{Eco}.

After standardization, the standardized economical corridor R'_{Eco} was obtained (represented in Fig. 6 as background grid coverage). R'_{Eco} contains a set of economically acceptable paths: the optimal economic path (represented in white) with the standardized value 0 and a range of more expensive paths, in decreasing order of preference (decreasing order in terms of increasing brightness of the map) to the limit of economical acceptance, with standardized value 1, corresponding to the outer corridor boundary. Note that each R'_{Eco} value represents a standardized value of distance to the optimal economic path (distance in the space of path alternatives).

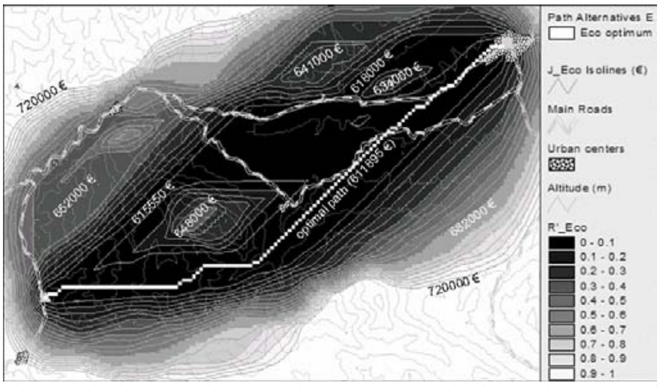

Fig. 6. Paths based on the economical corridor with background coverage of R'_{Eco} and J_{Eco} cost isolines (in €).

B. Path Corridor for the Environmental interest Group

Following the steps of block B in Fig. 1, the *Env* chose criteria coverages and then set geographical attributes for each criteria map. For this illustrative case study, three different environmental criteria were selected and the patterns of attributes set:

- Criterion map $C_{PA,Env}$: map of environmental protected areas according to regional environmental protection plans. These maps include sensitive areas of flora and fauna and sensitivity to regions with high visual impact. The preference-tolerance attributes were based on the value indexes of regional environmental protection plans.
- Criterion map $C_{DI,Env}$: map for proximity to inhabited areas. For attribute specification, low tolerance was specified for paths very close to urban areas; tolerance increased until a specified distance from urban center boundaries and then decreased gradually for distances further away from this length. The purpose was to concentrate the impact of overhead power lines near suburban areas but not too close to urban center cores. Fig. 2 shows a pattern analogous to the actual pattern for this criterion map.
- Criterion map $C_{DR,Env}$: map for proximity to roads. The attributes associated to this criterion had a high preference for paths near road infrastructures in order to concentrate the impact of roads and power lines in the same geographical areas. Fig. 3 shows a pattern similar to the actual pattern for this criterion map.

Following III.B, the *Env* assigned values on a scale from 0 (most preferred locations) to 1 (least tolerable locations) to its criteria maps and then the DAS reclassified and standardized them to obtain the $T'_{PA,Env}$, $T'_{DI,Env}$ and $T'_{DR,Env}$ attribute maps.

The aggregation of the attribute maps required the definition of criteria weights found by the pair-wise weight definition methodology. The pair-wise weights were selected by the *Env* based on the geographical patterns of the pair-wise aggregation (as in III.B for the pair of criteria $C_{DI,Env}$ and $C_{DR,Env}$). After applying this methodology, the definite values ($z_{p,selected}$ and $z_{q,selected}$) selected for the pair-wise criteria weights for each pair combination of criteria were: (z_{DR}=0.4 and z_{DI}=0.6), (z_{DR}=0.2 and z_{PA}=0.8), and (z_{DI}=0.3 and z_{PA}=0.7).

By applying the optimization procedure described in equation (3), the DAS obtained the following adjusted values for criterion weights: CW_{DR}=0.157, CW_{DI}=0.249 and CW_{PA}=0.594. Then the DAS produced the attribute map aggregations, following equation (4), to obtain the aggregate attribute map T_{Env} shown in Fig. 7.

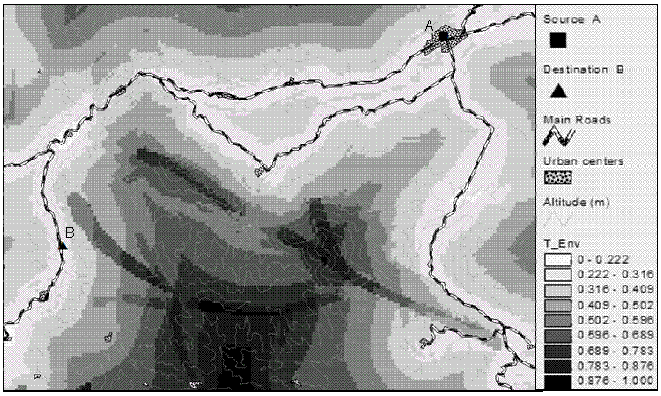

Fig. 7. Aggregated attribute map T_{Env} for the environmental interest Group.

The application of the DP optimization algorithm produced the standardized environmental path corridor R'_{Env} shown in Fig. 8, where R'_{Env} is represented as background grid coverage, and preferred paths are represented by darker colors. The environmental optimal path (represented in white) ran close to the main road. There were some other regions of the environmental path corridor that followed off-road paths close to the economical optimal path of the *Eco*, but these were paths with low-middle range (R'_{Env}=0.5) environmental preference. The lighter regions in R'_{Env} correspond to alternative paths farther from the environmental optimal path.

C. Efficient path compromises for power line installation

The DAS applied the DP optimization algorithm to the global utility function $F_{GWEco,GWEnv}$. Thus, Group corridors R'_{Eco} (Fig. 6) and R'_{Env} (Fig. 8) were linearly aggregated by the corresponding group weights GW_{Eco} and GW_{Env}. As explained in III.C, the group weights were set by the DAS, systematically generating all the weight combinations for a given discretization step. In this case study, the discretization step was established in 0.1. With this step value, there were eleven weight combinations and the corresponding eleven "alternative scenarios": Alternative Scenario 1 (AS1) for GW_{Env}= 0.001 and GW_{Eco}= 0.999; Alternative Scenario 2

(AS2) for GW_{Env}= 0.1 and GW_{Eco}= 0.9; and so on until Alternative Scenario 11 (AS11) for GW_{Env}= 0.999 and GW_{Eco}= 0.001.

Fig. 9 shows the eleven efficient path alternatives (with white raster paths identified by a circled number) corresponding to the eleven alternative scenarios from AS1 through AS11. The background grid in Fig. 9 is an example of one of the eleven global utility functions $F_{GWEco,GWEnv}$, in this case for GW_{Eco}= 0.5 and GW_{Env}=0.5. Notice in Fig. 9 that there are only three main path variants: efficient path alternatives numbers 10 and 11 (Alternative Scenarios AS10 and AS11), near the optimal path of the *Eco*; efficient path alternatives 1 to 5 (Alternative Scenarios AS1 to AS5), near the optimal path of the *Env* running near the road; and efficient path alternatives 6 to 9 (Alternative Scenarios AS6 to AS9), with paths between the two optimal alternatives of the two interest Groups. Table I summarizes the characteristics of each efficient path alternative; the "mean" value of R'_{Env} (or R'_{Eco}) represents the distance, measured in the space of path alternatives, to the optimal path of the *Env* (or the *Eco*).

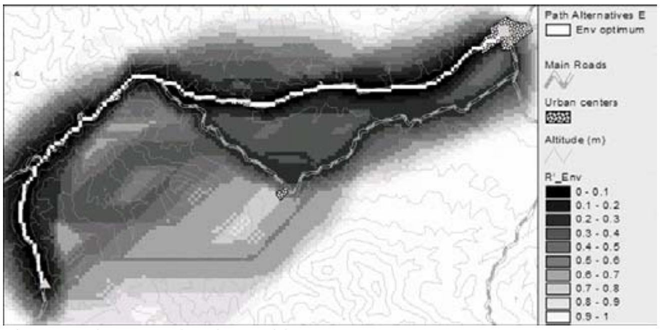

Fig. 8. Environmental paths corridor R'_{Env}.

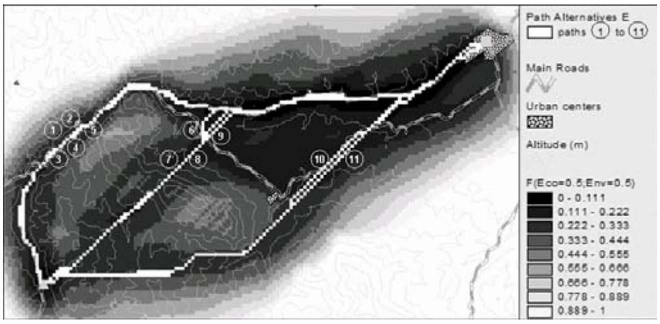

Fig. 9. Efficient paths alternatives $E_{GWEco,GWEnv}$.

TABLE I – CHARACTERISTICS OF THE POWER LINE PATH ALTERNATIVES

Alternative scenario	Mean R'_{Env}	Mean R'_{Eco}	Line cost (€)	Line length (km)	Cost (€/km)
AS1	0.0000	0.2206	635743	19.39	32787
AS2	0.0005	0.2183	635494	19.15	33185
AS3	0.0008	0.2161	635256	19.05	33347
AS4	0.0029	0.2147	635105	18.80	33782
AS5	0.0033	0.2137	634997	18.90	33598
AS6	0.1447	0.0333	615495	16.23	37923
AS7	0.1534	0.0284	614965	16.05	38316
AS8	0.1572	0.0267	614781	15.96	38520
AS9	0.1603	0.0262	614727	15.95	38541
AS10	0.3950	0.0009	611992	16.06	38107
AS11	0.4144	0.0000	611895	15.88	38532

Fig. 10 shows the set of efficient path alternatives mapped for criteria R'_{Env} and R'_{Eco}. Note that the typical heterogeneity of the terrain now gives rise to the geographical overlapping of efficient paths suggested by the DAS, limiting and simplifying the analysis of efficient alternatives in the negotiation process.

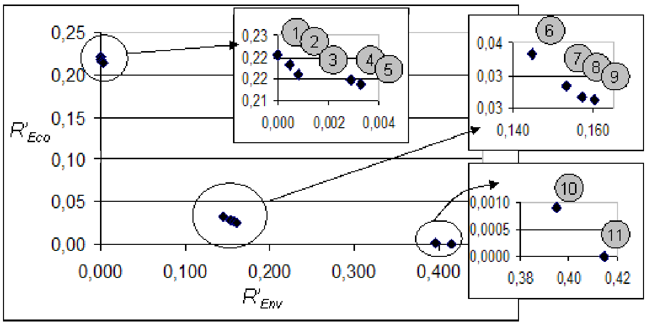

Fig. 10. Efficient path alternatives mapped in R'_{Env} and R'_{Eco}.

Path alternative 11 corresponds to the economical optimal path (611895 €) also obtained previously in IV.A. Path alternative 10 (611992 €) is close to the optimal economical solution. Path alternatives 6 to 10 also present relatively low costs (almost 615000 €); however, path alternatives 1 to 5 have significantly higher costs (almost 635000 €). Path alternatives 1 to 5 have a length of almost 19 km and the other alternatives approximately 16 km. Note that the worst economic alternatives (1 to 5) have a lower cost per kilometer, but their longer path lengths result in higher power line costs with respect to the other alternatives.

V. CONCLUSIONS

This paper has presented a new multi-criteria Decision Aid System (DAS) for line path selection based on economic and environmental corridors. It uses a novel DP optimization algorithm (geospatial Dynamic Programming algorithm) to find optimal paths on a GIS platform under suitable weighting techniques, as well as visual and representation capacities typical of GIS. The aim of the DAS is to determine the multi-criteria efficient line paths (non-dominated or Pareto optimal) that are best compromises regarding the two optimal line paths of an economic and an environmental interest group. Therefore, the DAS specifically produces a set of efficient paths without evaluating a huge number of possible paths between the origin and the destination of a new power line. The following negotiation process among Groups should become simpler because the Groups may now concentrate on achieving an agreement with regard to the definite selection of one of the efficient paths provided by the DAS.

The DAS methodology comprises two stages: first, the DAS helps the Groups to define their own criteria (various economic criteria and diverse environmental criteria), the corresponding attributes and the processes of their aggregation to discover, using a DP algorithm, the economic and environmental path corridors; second, the DAS systematically applies a suitable set of weights on these two corridors to obtain GIS coverages of the global utility function for both Groups and then to suggest the efficient paths by once again using the DP algorithm.

The DAS methodology and the case study presented in this paper have been described for two Groups involved in a negotiation process for the project of a new line, but the DAS can be used for more Groups. The DAS has been initially applied in the path selection of new overhead power lines, although it can be used for underground line applications.

Several innovations relating to the problem of line path selection have been achieved:

a) A way of merging the preferences of different Groups with conflicting interests in order to facilitate the following negotiation processes, allowing consensual path solution.
b) Based on the concept of elementary environmental impacts, the methodology finds an optimal path corridor under environmental and social criteria.
c) The Decision Aid System is integrally implemented in a GIS platform providing high geographical realism for problem modeling and facilitating the visual interaction between the Groups and the DAS.
d) The Decision Aid System and path optimization are merged in a single process, enabling just one set of efficient path alternatives to be obtained directly.

This new methodology and approach used for implementation have resulted in an automated planning tool that facilitates the understanding of the problem and its solutions, providing a valuable aid for identifying consensual or compromise solutions and assisting the decision process in relation to power line installation.

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VII. Biographies

Cláudio Monteiro was born in France, on March 14th, 1968. He received his Licenciado and MSc. and Ph.D degrees from FEUP in 1993, 1996 and 2003, in Electrical Engineering and Computers. In 1993 he joined INESC as a researcher in the Power System Unit.

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