GIS Spatial Analysis Applied to Electric Line Routing Optimization

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***Abstract*—This paper presents a new methodology for automated route selection for the construction of new power lines, based on geographic information systems (GIS). It uses a dynamic programming model for route optimization. Environmental restrictions are taken into account together with all of the operating, maintenance, and equipment installation costs, including a new approach to the costs associated with the slope of the terrain crossed by the power lines. The computing and visual representation capacities of GIS are exploited for the selection of economic corridors, keeping the total costs under a threshold imposed by the user. Intensive simulation examples illustrate the power and flexibility of the proposed methodology.**

***Index Terms*—Decision-making, decision support systems, geographic information systems, power distribution planning, power transmission planning.**

I. INTRODUCTION

THE MANUAL design of a new electric power line is a time consuming and costly activity that requires massive and detailed spatial information and project engineers experienced in the terrain. It usually involves two steps: line routing selection or equipment placement determination, and detailed sizing of all the elements. Electric power-line routing is an engineering task that optimizes the equipment installation and maintenance costs subject to geographic, environmental, social, and legal constraints. Thus, routing can be defined as the previous stage to the design of a new electric power line, where the planner decides the path and areas crossed by the line taking into account the existing constraints.

The spatial nature of some of the aspects involved in power-line routing leads to a compromise between a straight line from one point to another and path deviation to avoid costly terrain, obstacles, or other intolerance criteria. The automation of the routing process integrates a detailed geographic modeling of the problem with information and expert knowledge in order to reduce both the time consumed and the gap between planning and erection and, therefore, to reduce efforts in the revision of the project [1]. It also allows studying in a short time multiple routing solutions and assessing solution robustness to uncertainties in problem variables.

Automated line design has been an active research field in the last decades, but most of the efforts have been made in the detailed sizing of all the elements of the new power line, and only a few references include approaches based on realistic geographic line routing. In early published works, geographic information systems (GIS) were identified as the proper computer platform to develop automated routing of underground residential distribution systems [1], [2]. Route selection was based on GIS geographic data manipulation capacity and took in account the essential geographic characteristics of the routing problem, although human designers had to interact with computer systems in order to generate and explore alternative options in the routing process.

Other approaches included an heuristic search algorithm for optimizing routes, reducing the space of feasible routing alternatives [3], or automating the search of the shortest path in street routes for underground feeder planning [4].

The integration of cost and environmental constraints into overhead transmission line routing was presented in [5], using satellite images to identify the areas that constitute an environmental constraint and giving different qualitative weights to each constraint. Routes were selected according to the shortest length and the least impact or weight on the region crossed by the line among an initial set of routing alternatives.

An automated distribution routing approach for rural areas was presented in [6], where the area studied to build a new electric line was divided into different cost regions according to the difficulty of building in each region. The obstacles or regions with high constraints to the construction of a new line were treated as infinite cost regions. A further approach with the same methodology, but using GIS, was presented in [7].

In the first approaches to line routing using GIS, the representation of geographic data in vector format was selected, and the different regions, existing infrastructure, and obstacles were represented as lines or polygons.

A distinct approach, based on the representation of geographic data in raster format, was used in [8] for distribution system planning, although the routing problem was ignored. In raster format, the area under study is split in a regular grid of cells where each cell contains a value of interest and a geographic position.

Other more recently published works consider the routing task as an optimization problem by defining an objective function to minimize but without using any specific format.

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The criterion for the selection of the optimal route for a new underground line is a function called impedance index [9], corresponding to a weighted length value of the proposed routes along the streets according to the characteristics of each segment of the route. In [10], the objective function is the cost (operation and installation) of the optimal distribution system routing, although no real GIS system is used, terrain costs and routing paths are not modeled in detail.

The main concepts of this paper form the basis for any optimal routing application, but the details included are mainly aimed at defining overhead line routing (for transmission, subtransmission, and primary distribution), without excluding underground lines. In the optimal routing process, operation, maintenance, and equipment installation costs are taken into account, including terrain costs and also installation costs associated with the slope of the terrain. The paper is focused on GIS spatial methodologies for a simple point-to-point overhead economic corridor selection for the new power line. This implies selecting an elongated area that includes the optimal line path (with the lowest economic cost) between two points as well as the surrounding areas defined by feasible power-line routes, keeping total costs (operation, maintenance, and investment) under a threshold imposed by the user; this bound usually leads to many suitable routing alternatives for power lines between two points, which determine the line economic corridor.

In this work, a real GIS platform is used for the selection of the minimum cost route as well as its economic corridor, where geographic data (installation, maintenance, operation costs, land use, etc.) and computing results are represented in raster format instead of vector format. The raster format allows adopting dynamic programming (DP) [11] for all of the studied geographic areas. An original application of advanced DP optimization to raster data is carried out in an iterative way for the selection of the optimal route path. Another innovative process developed is a new directional routing formulation to model the additional routing costs caused by terrain slopes (that depend on the direction followed), as well as a two-directional approach to the routing problem (origins and destinations act as starting points of the routes in the first stages of the proposed methodology) for route path selection.

II. DATA STRUCTURES

The adoption of GIS vector data structures is common in network problems based on lines, edges, and nodes (under a synthetic network methodology). However, the actual terrain information (slopes, soil types, terrain costs, geographic restrictions, obstacles, etc.) is not suitably associated with nodes and lines, although it can be associated with small areas represented as polygons or elementary cells. This feature is a reason to optimize the paths directly in terrain-oriented formats ("GIS raster" structure) instead of using a synthetic network methodology. GIS raster structures are basically a regular matrix of square cells where each cell represents an elementary area and position. The detail of the geospatial analysis depends on the size of the elementary cell (resolution). With this structure, the spatial analysis is based on matrix operations, where the matrix corresponds to a geographic coverage (terrain costs, terrain slope, soil types, and other aspects), and the information of each matrix element corresponds to numerical information associated with the corresponding location (cost of traversing the location, average slope surrounding the location, etc.).

In GIS raster routing, all costs must be associated with terrain surface. When low resolution (e.g., cell area of 1×1 km, that is, 1 km of resolution r) is used, the costs of the sections of overhead lines, including conductors, insulators, and support structures are associated with a cell area of the map grid without specifying the location of the support structures (towers). This concept simplifies the routing process by assuming that the cost of the overhead transmission line components is uniformly distributed along the path (a cost per kilometer), similar to an underground cable routing problem. For corridor routing purposes, this simplification is assumed, even if high-resolution geospatial analyses (e.g., cell area of 5×5 m, that is, 5 m of resolution r) are used. The cost of each component is associated with the cell location that contains the geographic feature that causes the cost (e.g., road, lake, or river locations have an associated additional cost due to the insulator reinforcement and other elements).

A relevant component of the cost per kilometer is related to the equipment of the line and is independent of the geographic features. This nongeographic cost component (NGC) is associated with the line that crosses the adjacent cells p_k and p_{k-1}, and leads to a straight line routing. Geography-dependent costs [many of them associated with terrain cross costs (TCC)] have a variety of causes. Several frequent causes (and the corresponding geographic cost) can be described as:

1) "Accessibility" costs: represented as grid coverages with additional costs for the equipment transportation, installation, and maintenance. They depend on the geographic location and are computed with minimum cost-distance spatial functions. Thus, GIS coverages with road and offroad crossing costs are needed to measure them.
2) Cost due to "specific characteristics" of the geographic area: other additional costs based on the soil type, land use, vegetation coverage, urban areas, corrosive areas near the shores, and high environmental impact areas are characterized by grid coverages with additional cost due to the ownership of the terrain, which depends on the actual usage of land and the estimation of land price for each usage. The vegetation coverage also causes an additional installation and maintenance cost of cutting and pruning. Furthermore, environmental restrictions can be considered as an external cost, a cost of substitution of overhead line for underground cable or an extremely high cost for impossible locations. Moreover, the soil type can provide maps with additional costs related to different costs of digging the tower foundations of overhead electric lines.
3) "Terrain complexity" cost: terrain slope and orographic complexity grids are needed to build a grid coverage of additional geographic cost relative to lines in flat terrains. Nonflat terrains involve higher towers, more tower units, and more dead-end towers. Thus, the complexity of the terrain can be evaluated by calculating average terrain slopes for geospatial analyses of several resolutions or calculating the gradient of the terrain.

4) "Wind speed" cost: wind speed maps are needed to obtain a grid coverage with costs associated with the reinforcement of the towers and foundations built to withstand high wind speeds (since higher wind speeds involve more expensive towers to support stronger mechanical strengths).
5) "Altitude" cost: costs associated with altitude and mountain ridges are needed as altitude defines several levels of icing probabilities that can involve more expensive towers to support stronger mechanical stress. Mountain ridges are also locations with higher costs associated with investments in electric protection equipment, like surge arresters, due to increased probabilities of lightning.
6) Cost due to "obstacles": roads, railways, rivers, telecommunication, and other power lines can be obstacles in routing design. Crossing these elements involves insulator reinforcements in the two side towers for mechanical and electrical safety reasons. This cost is associated with crossing cell elements, and represents a geographic cost to take into account. The proximity to other geographic obstacles or infrastructures (or other facilities) involves additional costs related to signalization equipment (e.g., near airports) or increased costs of obstacle crossing (e.g., lakes or dams).

Most of these geographic costs are modeled in the routing model (under a raster structure) as costs of crossing the cells. The geographic cost leads to nonstraight paths and, consequently, to additional costs associated with deviation towers. The costs due to direction changes are modeled in the routing algorithm of this paper. Additional costs associated with the slopes are considered in two different ways: as a cell crossing cost and as a directional slope cost modeled in the routing algorithm. The information required is:

- information associated with origins, describing the location and the cost of departure from each origin cell p_0 (cost of departure, i.e., $g_0(p_0)$, associated with the origin cell p_0);
- information about the cost of crossing an elementary cell $p_k, (c_{p_k}^{\mathrm{TCC}})$, where most of the geographic costs (previously presented) are included;
- direction change cost $(c_{p_k,p_{k-1},p_{k-2}}^{\mathrm{DCC}})$ stored in a geographic grid containing information about the additional cost if the direction changes at a particular point p_{k-1}, between p_k and p_{k-2};
- digital terrain model necessary to evaluate the costs associated with the local terrain slope $(S_{p_k,p_{k-1}})$ between the neighboring cells p_k and p_{k-1}. Crossing the same cell p_k (in different directions) toward different neighboring cells p_{k-1} may result in different slope costs $(c_{p_k,p_{k-1}}^{\mathrm{SC}})$;
- information about nongeographic cost $c_{p_k}^{\mathrm{NGC}}$ associated with any cell p_k.

III. METHODOLOGY

This section describes the proposed GIS methodology for power-line routing having DP as the core optimization method. Specific tools to manage and build spatial or geographic cost databases are designed to embed DP into GIS. The results are the optimal route to install a power line in a geographic region, given a definition of the origin of that line, and the expected optimal cost of construction.

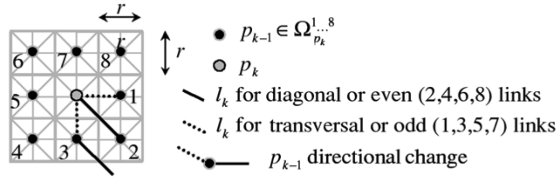

Fig. 1. Data structure elements associated with links.

DP is a suitable optimization technique for using with GIS raster structures (i.e., geographic coverages) in line routing. In DP terminology [11], GIS raster line routing is based on a set of elementary cells with links between neighboring cells in a particular order (stage) along the path or route. Each cell maintains the record of an accumulated transition cost, evaluated at a particular point (state) of the calculation process along the path between the origin of the route and that cell; the optimal path between two locations (optimal decision policy) is the sequential aggregation of optimal elementary transitions or links (optimal decision policies that lead to new states of the following stages) between neighboring cells from the origin to the end of the route.

The Bellman principle of optimality states that an optimal policy must contain only optimal subpolicies, and each optimal subpolicy is independent of past optimal subpolicies. Thus, DP involves breaking up a complex problem into simpler subproblems so that the optimization process can be systematically carried out by optimizing recursively the subproblems in an iterative process. The sequence of raster cells along a path represents the stages in the DP terminology and the minimization of the accumulated transition cost between two neighboring cells is the optimization subproblem. The DP calculation process selects the consecutive stages by choosing the cell links that lead to a minimum accumulated transition cost for each state of this process.

First, let us define a discrete two-dimensional (2-D) space $\Omega = \{(x,y) : x = 0,\ldots,H; y = 0,\ldots,V\}$ that represents the GIS geographic coverage, where (x,y) represents the elementary cell (geographic location) that can be a vertex in a path.

The set $P = \{p_0,\ldots,p_k,\ldots,p_K\} = \{(x_0,y_0),\ldots,(x_k,y_k),\ldots,(x_K,y_K)\} = \{l_1,\ldots l_k,\ldots,l_K\}$ is the geographic path composed of $K+1$ vertices. Each vertex is a cell of coordinates (x_k,y_k) in the 2-D space Ω. The set of vertices creates a line by following a sequence of K stages labeled with the index k. The line segments l_k are the links between the vertices p_{k-1} and p_k. Adjacent stages must be necessarily associated to neighboring cells in the space Ω. Thus, the space Ω is organized as a rectangular matrix where each cell can be linked to eight neighboring cells $\Omega_{p_k}^{1\ldots8}$, as shown in Fig. 1.

In the computational process, the links that provide the optimal route (i.e., the minimum accumulated cost that links each cell with the origin) are saved in a directional grid coverage with a code in each cell with information on how to move to the origin. The assigned code is associated with the corresponding directions from one of the eight

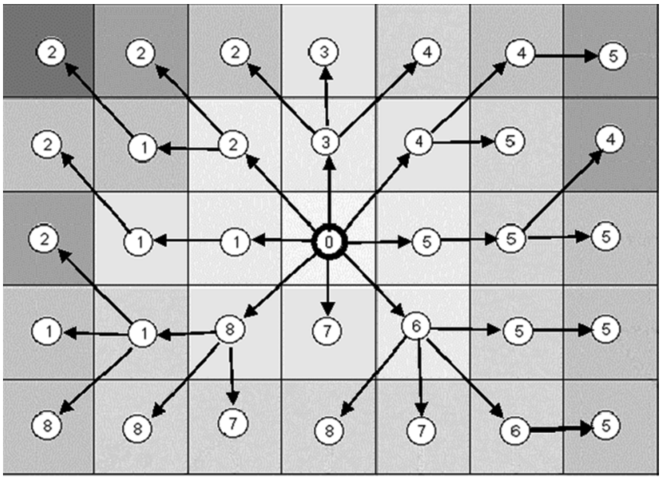

Fig. 2. Radial path structure for back-link path tracing.

vertices p_{k-1} to the vertex p_k on the mariner's compass $\{(1,2,3,4,5,6,7,8) \equiv (\mathrm{W},\mathrm{NW},\mathrm{N},\mathrm{NE},\mathrm{E},\mathrm{SE},\mathrm{S},\mathrm{SW})\}$, as shown in Fig. 1 and the example of Fig. 2. The origin cells are set to code 0.

A transition cost given by $f(l_k)$ is associated with each line segment l_k that links two neighboring cells. This cost is a fixed value initialized at the beginning of the computation process and evaluated to accumulate the routing cost of a power line.

The transition cost between two neighboring cells (p_k and p_{k-1}) is computed based on the elementary information associated with both cells and their relative position (as well as, obviously, the cell resolution r). This cost can be obtained from three cost components:

1) nongeographic costs (NGCs) $c^{\mathrm{NGC}}_{p_k}$, independent of the position of the cell but dependent on its dimensions (i.e., the resolution r of the raster);
2) slope costs (SCs) $c^{\mathrm{SC}}_{p_k,p_{k-1}}$, or costs associated with the local slope of the terrain between p_k and p_{k-1} (a geographic cost that also depends on the resolution r);
3) terrain cross costs (TCC) $c^{\mathrm{TCC}}_{p_k}$ and $c^{\mathrm{TCC}}_{p_{k-1}}$, with the remaining geographic costs (described in Section II) associated with each particular cell of the grid when a specific power line crosses that cell. In the cost model, this part of the transition cost is shared between both cells;
4) it is also possible to set a direction change cost (DCC) $c^{\mathrm{DCC}}_{p_k,p_{k-1},p_{k-2}}$, for each geographic location if the direction path changes between consecutive links l_k, l_{k-1} (i.e., between vertices p_k, p_{k-1}, and p_{k-2}).

With the exception of SC, all of the cost components are presented as user inputs in GIS grid raster coverages. SCs are computed by the GIS, using a digital terrain model and a lookup table with the costs associated with each slope level. DCC are penalization costs used to force nondirection changes in some geographic regions. With the exception of DCC, all of the costs are costs per kilometer $c^{\mathrm{LU}}_{p_k,p_{k-1}}$ in (1), and this is why the resolution r is used in (2) and (3).

An important aspect of the inclusion of the SC component is that the cost of crossing a cell is not the same in every direction, which allows the algorithm to find better paths by following smoother slopes.

The cost $f(l_k)$ is computed in (2) if l_k is a diagonal link (the p_{k-1} code is an even code, see Fig. 1) and in (3) if l_k is a transversal link (the p_{k-1} code is an odd code, see Fig. 1)

$$c^{\mathrm{LU}}_{p_k,p_{k-1}} = \left(c^{\mathrm{NGC}}_{p_k} + c^{\mathrm{SC}}_{p_k,p_{k-1}} + \frac{c^{\mathrm{TCC}}_{p_k} + c^{\mathrm{TCC}}_{p_{k-1}}}{2} \right) \quad (1)$$

$$f(l_k)_{\mathrm{even}} = \sqrt{2}\, r c^{\mathrm{LU}}_{p_k,p_{k-1}} + c^{\mathrm{DCC}}_{p_k,p_{k-1},p_{k-2}} \quad (2)$$

$$f(l_k)_{\mathrm{odd}} = r c^{\mathrm{LU}}_{p_k,p_{k-1}} + c^{\mathrm{DCC}}_{p_k,p_{k-1},p_{k-2}}. \quad (3)$$

A stage k and a state t are associated with each cell (x_k, y_k) that can be a vertex of the route. The stage index k denotes the set of cells that must be crossed following the cheapest path from the origin (x_0, y_0) to the vertex p_k (i.e., the cell (x_k, y_k)). The state t is an index in the computation sequence that represents the iteration number; in our formulation, it is associated with the accumulated cost $g_t(p_k)$ to reach the cell (x_k, y_k) in this iteration t by crossing all of the cells in the path. The cells in the path are not fixed at a particular stage, since one cell can change its membership to this stage along the iteration process.

For each cell belonging to Ω, the cost $g_t(p_k)$ for the stage k and the state t is given by

$$g_t(p_k) = g_{t,t-1}(p_{k-1}) + f(l_k) \quad (4)$$

where $p_{k-1} \in \Omega^{1\ldots8}_{p_k}$, that is, p_{k-1} is one of the eight neighboring cells around the path vertex p_k; $g_{t,t-1}(p_{k-1})$ plays the typical role of a buffer in a recursive equation (i.e., the accumulated cost in the vertex p_{k-1} at the previous state $t-1$, which can be updated depending on the iteration process; and $f(l_k)$ is the transition cost of each link between p_k and p_{k-1}.

Let us consider that the cost of a line from the origin to a specific cell location corresponding to the stage $k-1$ is the accumulated cost $g_{t,t-1}(p_{k-1})$, and that $f(l_k)$ is the cost of linking stages k and $k-1$. According to DP principles, the minimum accumulated cost from a given origin to one neighboring cell of the stage $k-1$, corresponding to stage k (that is, a point p_k), is given by ${}^*g_t(p_k)$, as shown in (5)

$$\begin{aligned} {}^*g_t(p_k) &= \min(g_{t,t-1}(p_{k-1}) + f(l_k)) \\ \text{s.t.} \quad & p_{k-1} \in \Omega^{1\ldots8}_{p_k}. \end{aligned} \quad (5)$$

The last optimal evaluated state of the cell $p_{k-1}, g_{t,t-1}(p_{k-1})$ can be computed in state t if this iteration index is updated, or in the previous state (iteration) $t-1$ if the value is not updated (this occurs if the previous state $t-1$ leads to a lower accumulation cost from p_0 to p_{k-1}). The origin cell p_0 has an associated predefined cost $g_0(p_0)$ which represents the fixed cost of departure from that origin cell.

The minimum accumulated cost is computed along the DP optimization process, not only on the routing path but also on the whole geographic coverage. This means that the routing optimization is performed between the origin cell and the rest of the cells in the geographic coverage. The coverage of the minimum accumulated cost in each cell of the geographic GIS coverage allows to create cost isolines that show cost increases as functions of the distance to a selected origin.

The path from the origin to each cell in the geographic coverage is stored in a directional raster coverage. For each cell, the code (1 to 8) represents the "back" link to the previous neighboring cell. This coding defines a radial path structure that covers the whole region and allows to trace the path from any destination cell to the origin. This means that each p_k cell is linked to only one p_{k-1} cell although each p_{k-1} can be linked to several p_k cells. Fig. 2 shows an example of this directional raster coverage which saves the directional codes to move from the origin (code 0) to each cell in a discrete 2-D space $\Omega = \{(x, y) : x = 0, \ldots, 6; y = 0, \ldots, 4\}$. The cell (0, 0) is located at the bottom left corner and the origin is located at (3, 2). Once the calculation process is over, to reach the cell located at (0, 2) from the origin location (3, 2) with the code 0, the optimal route goes first to SW (code 8), then to W (code 1), and, finally, to NW (code 2).

The possible origins of a path are presented as user inputs by GIS point coverages or by line (shape) coverages. If the user defines several origins, the routing algorithm finds the optimal path (lowest cost) to the closest origin, and the computational results show the whole 2-D space Ω divided in radial areas optimally served by their own origin. Moreover, if the origins are located in a power line, the DP algorithm finds the optimal path from each cell of Ω to the closest (from a cost-effective point of view) point of this line.

To obtain the expected results, it is necessary to collect cost data (both geographic and nongeographic) for the construction of power lines, and to arrange them into GIS in practical spatial databases and map (grid) formats. Then, they can be managed by the designed DP algorithm.

The algorithm of the iterative DP procedure applied to "GIS raster" line routing is as follows:

1) Establish the resolution r of the studied area to create cells ($p_k \in \Omega$) of dimension r. Initialize the accumulation cost matrix $g_0(p_0)$ with a simple initial state (for example, only the cost of "going out" the origin/origins, with "no data" in the rest of the cells). Digital terrain model (DTM) and nongeographic costs c^{NGC} are available;
2) for each cell ($p_k \in \Omega$) for the state t;
3) for each neighboring cell ($p_{k-1} \in \Omega_{P_k}^{1\ldots 8}$), for the state t if updated, or for the state $t-1$, otherwise;
4) compute the slope $S_{p_k, p_{k-1}}$ with the DTM;
5) compute the slope cost $c_{p_k, p_{k-1}}^{\mathrm{SC}}$;
6) compute the terrain cross cost $c_{p_k}^{\mathrm{TCC}}$ and $c_{p_{k-1}}^{\mathrm{TCC}}$;
7) compute the direction change cost, if applicable $c_{p_k, p_{k-1}, p_{k-2}}^{\mathrm{DCC}}$;
8) compute the transition cost $f(l_k)$;
9) compute the accumulated cost $g_t(p_k)$;
10) go to following cell ($p_{k-1} \in \Omega_{p_k}^{1\ldots 8}$) of the eight neighboring cells *(Cycle to 3)*;
11) select cell ($p_{k-1} \in \Omega_{p_k}^{1\ldots 8}$), with its code, as "back" link cell leading to the minimum of $g_t(p_k), {}^*g_t(p_k)$;
12) in association with the minimum of $g_t(p_k)$, that is ${}^*g_t(p_k)$ store the minimum cost path, for the state t and the stage k for the cell p_k;
13) go to following cell ($p_k \in \Omega$) in the geographic coverage. (*Cycle to 2)*;
14) compare ${}^*g_t(p_k)$ with ${}^*g_{t-1}(p_k)$ for the whole coverage;
15) go to 2 for a new iteration until no changes are identified in the whole coverage (checked in step 14).

The first step (1) is aimed at defining the resolution of the calculation grids, initializing ($t = 0$) the accumulated cost grid, and arranging data for subsequent calculations. Between steps 2 and 13, the computation of the accumulated cost grid is performed for each cell of the grid (only the origins are initialized); then the accumulated costs are calculated from the origin to every cell at each iteration. For steps 3 to 10, the algorithm computes the transition cost between a central cell and the eight neighboring cells, including all of the cost components. In steps 11 and 12, the transition sequence between the neighboring cells (which defines the path with the minimum cost) is selected as "back" link. In steps 14 and 15, the algorithm starts the following iteration and stops when no changes between iterations are detected. At previous iterations, cost paths can be selected by using other origins that do not lead to the global minimum cost path. When no changes are detected between successive iterations, we have reached the minimum accumulated cost path to each cell in the coverage and selected the "back" link cell leading to the least expensive path between the origin and the destination.

IV. POWER-LINE ECONOMIC CORRIDORS

Economic corridors are elongated areas that define the geographic bounds of potential optimum or near-optimum paths. Line corridors show the sensitivity of the electric power-line routing to cost-associated geographic aspects and give a visual idea of the geographic uncertainty of the routing.

The economic corridor routing methodology assesses the additional costs related with a path deviation from the optimal path. The relationship between the spatial deviation from the optimal path and the corresponding additional costs gives a visual idea of the geographic cost sensitivity to route changes.

The spatial computation of economic corridors involves computing the optimal cost path within a discrete 2-D space Ω from an origin p_A to a destination p_B, forcing the path to pass through a given point p_k. This point p_k can be on or near the optimal path $\{p_A, \ldots, {}^*p_k, \ldots, p_B\}$. This is achieved by computing the optimal path of two path segments between an origin p_A and a partial destination p_k, and then computing the optimal path from an origin p_B to the same partial destination p_k. The cost associated with the path $\{p_A, \ldots, p_k, \ldots, p_B\}$ between p_A and p_B (forcing it to pass through p_k) is the sum of the minimum cost path of the segment $\{p_A, \ldots, p_k\}, {}^*g_{p_A}(p_k)$ and the minimum cost path of the segment $\{p_B, \ldots, p_k\}, {}^*g_{p_B}(p_k)$. This cost $h_{p_A, p_B}(p_k)$ can be computed for all of the cells p_k, where $p_k \in \Omega$. Thus

$$h_{p_A, p_B}(p_k) = {}^*g_{p_A}(p_k) + {}^*g_{p_B}(p_k). \tag{6}$$

The economic corridor is defined within a boundary region, where the cost of deviation from the optimal path is lower than a maximum value $h_{\max}$, while the optimal path between A and B $\{p_A, \ldots, {}^*p_k, \ldots, p_B\}$ has the same and minimum value

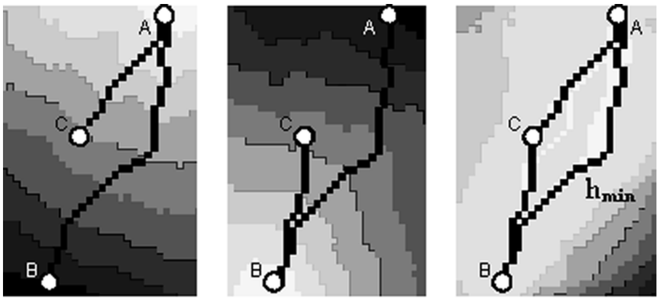

Fig. 3. Path computation.

$(h_{\min})$ at each vertex $^*p_k$ of the optimal route. Therefore, the economic corridor is defined by

$$p_k \in \Omega : h_{\min} \le h_{p_A,p_B}(p_k) \le h_{\max}. \tag{7}$$

If a cell has the minimum value $h_{\min}$ then it belongs to the optimal path, and if its value is $h_{\max}$, then it belongs to the bound cells of the corridor.

Fig. 3 shows the calculation sequence of a power-line path belonging to the corridor between two points A and B.

1) The optimal paths that connect each cell of the area with the origin A in terms of economic costs are calculated in the first step, as shown on the left side of Fig. 3. The optimal "back" line that links the point C (C represents a generic location) with the origin A is represented as a black line; and another black line represents the optimal "back" line that links the point B with the origin A. Note the accumulated cost isolines in the background: clearer areas have lower associated accumulated costs than darker ones.
2) In the second step (in the middle of Fig. 3), the previous step is repeated but using B as the origin instead of A. The optimal "back" line that links the point A (accumulated cost $h_{\min}$) with the origin B (null accumulated cost) passes through the same locations as the optimal "back" line obtained in step 1) that links the point B (accumulated cost $h_{\min}$) with the origin A (null accumulated cost).
3) In the third step (on the right side of Fig. 3), the geographic coverages obtained in the two previous steps are added to obtain the cost of the electric power-line path between A and B passing through C. These cell locations with costs lower than or equal to $h_{\max}$ define the economic corridor. Cell locations with the value $h_{\min}$ define the optimal path.

V. COMPUTATIONAL RESULTS

The DP routing method was implemented in C++ and embedded in a GIS application (ArcView) and successfully tested in selecting optimal point-to-point line routings, as well as in finding economic corridors between two points for overhead lines. Furthermore, the technique can be extended to underground line routing applications.

In this section, we present results from test cases in selected regions in La Rioja, Spain. These results in raster format, corresponding to power-line economic corridors, contain multiple routing alternatives for a new line between specific origin and destination points. This set of feasible economic routing alternatives can be the starting point for a negotiation process among different agents involved in the final selection of power-line routes (utilities, local authorities, social groups, environmentalist, etc.) in order to find suitable routing solutions based on consensus.

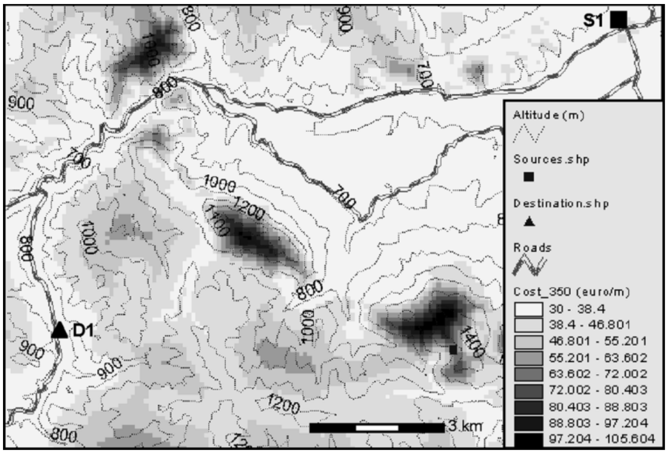

Fig. 4. Cost associated "with crossing each cell" for 66-kV overhead power lines with an ACSR-350 conductor type.

A. *Applications of "Point-to-Point Optimal Line Routing"*

We used a GIS application to support the routing modeling of 66-kV overhead lines for several different conductor types (sizes) between one source and one destination. The map in Fig. 4 shows the location of the source (S1, ■) and of the destination point (D1, ▲). In the following paragraphs, we will describe the computational results obtained.

For a 66-kV overhead power line with ACSR-350 conductors, the costs associated "with crossing each cell" are given in Fig. 4. These costs have a nongeographic component and a geographic component that depends on the terrain, obstacles, environmentally protected areas, and other characteristics. The sum of the two components is shown in the background coverage (raster format) in Fig. 4 (Cost_350 euro/m in the legend of the figure). This coverage gives the cost (euro/m or €/m) for the line, associated with crossing each elementary cell in the optimal routing process.

In this coverage, the geographic impact of the crossing cost is visible. Darker regions represent higher costs influenced by the distance to main and secondary roads, land use (and the corresponding land price) or/and the distance to environmentally protected areas. There is an additional component of the cost that depends on the slope of the route. The routing algorithm computes the local slope for each cell in each direction and associates with it an additional cost from a lookup table (with higher costs for higher slopes). Fig. 4 shows the elevation contour lines: higher lines densities correspond to higher slopes.

Fig. 5 shows the computational results for a 66-kV overhead line with ACSR-350 conductors between the source point (S1) and the destination point (D1). Note that the optimal route (the darkest line) obtained in the optimization crosses the regions with the lowest cost and avoids areas with high geographic costs.

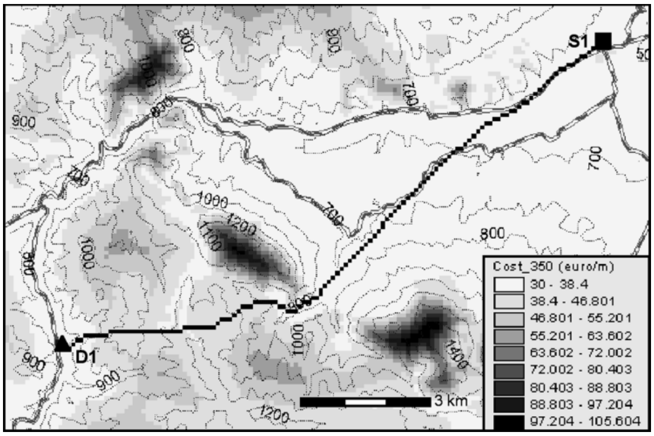

Fig. 5. Optimal route for a 66-kV overhead power line with an ACSR-350 conductor type.

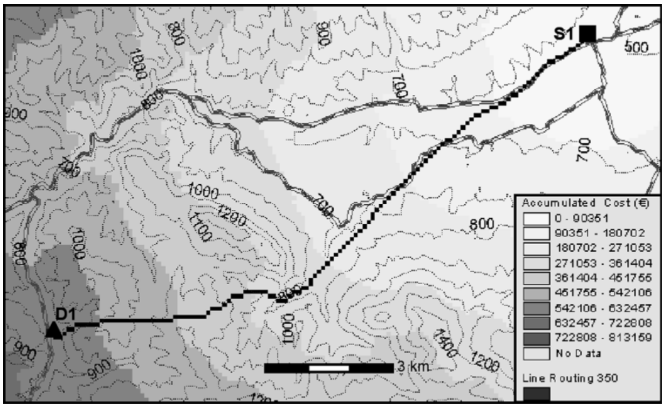

Fig. 6. Accumulated cost coverage for a 66-kV overhead power line with an ACSR-350 conductor type.

Note also the influence of the slope in some regions with a geographically complex terrain. Furthermore, the optimal routing in high-slope locations determines a nonperpendicular crossing of the contour lines.

The background coverage shown in Fig. 6 (as accumulated cost (€) in the legend of the figure) is the cost coverage described in Section III, which provides the minimum cost of building a power line with ACSR-350 conductors from a source (origin) S1 to each location (cell) in the geographic coverage. Obviously, locations far from the source imply higher costs. However, nonconcentric curves due to the influence of geographic areas with relatively high crossing costs can be identified by observing areas with equal costs. The optimal routing is perpendicular to the isolines of the accumulated costs. The optimal total cost for the line routing S1-D1 is 596 742 €. This value can be obtained for the destination point D1 with the accumulated cost coverage, as shown in Fig. 6.

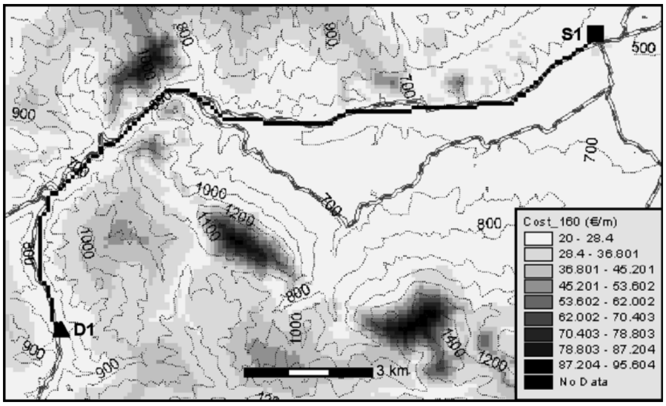

Fig. 7. Optimal route and costs associated “with crossing each cell” for a 66-kV overhead power line with an ACSR-160 conductor type.

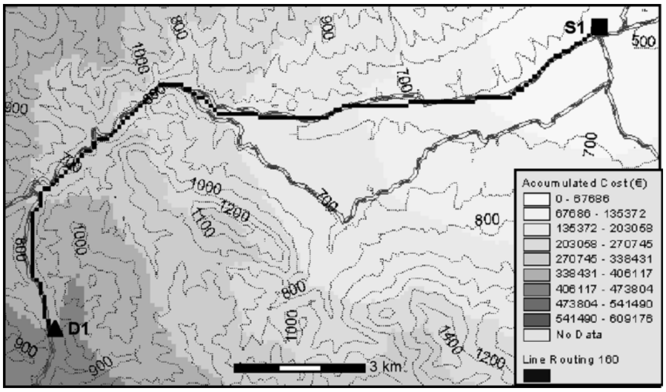

Fig. 8. Accumulated cost coverage for a 66-kV overhead power line with an ACSR-160 conductor type.

Fig. 7 shows the computational results of the point-to-point route between the origin S1 and the destination D1 for a 66-kV overhead electrical line with another conductor type ACSR-160. The costs associated “with crossing each cell” are represented with different shades of gray, as shown in the legend of Fig. 7. The geographic component of this cost is the same as the one we have explained before, as it is similar to the 66-kV overhead line of the previous case (ACSR-350). However, the nongeographic cost of the equipment is significantly lower (about 10 000 €/km less expensive than that of the ACSR-350 conductor type).

The computational results show that the optimal route changes significantly if we compare Fig. 7 with Fig. 5. The route S1-D1 changes path and gets closer to the neighboring road due to the smaller weight of equipment costs when compared to geographic costs. This illustrates a case where an extended route in a cheaper terrain is preferable to a shorter route in a more expensive terrain. Furthermore, the influence of the slope is clearer for the power line with ACSR-160 conductors: the best route in this case follows the elevation contour lines more than in the previous case with ACSR-350 conductors.

Fig. 8 shows the accumulated cost coverage (accumulated cost (€) in the legend of the figure) with the lowest values associated with the 66-kV ACSR-160 line. The optimal total cost between points S1 and D1 is 406 648 €. If the patterns of the accumulated cost coverages for the two cases (ACSR-350 in Fig. 6 and ACSR-160 in Fig. 8) are compared, we can observe higher irregularities for the line with ACSR-160 conductors, caused by the larger influence of geographic costs.

B. Applications of “Power Line Economic Corridors”

The previous examples show that is possible to obtain an optimal routing path for a new power line even in areas with complex geographic characteristics. However, cost uncertainties

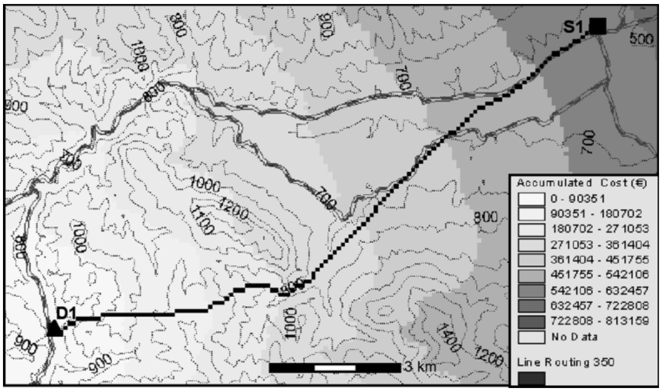

Fig. 9. Accumulated cost coverage for a 66-kV overhead power line with an ACSR-350 conductor type and D1 as origin.

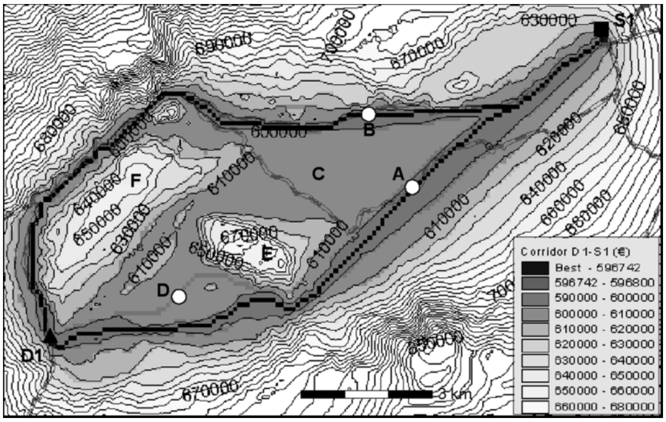

Fig. 10. Power-line economic corridors for 66-kV overhead electrical lines with an ACSR-350 conductor type between S1-D1.

can lead to changes in routing paths. In fact, at this stage of the electric power-line design, it is more efficient to select an economic corridor and study the corresponding uncertainties than analyze the individual possible solutions.

With the methodology described in Section IV, we have also computed the economic corridors for a path from the source S1 (■) to the destination D1 (▲) for a 66-kV overhead power line with ACSR-350 conductors. Remember that the computing process implies three routing optimization steps: First, we have to compute the accumulated cost coverage from point S1 (one extreme of the path) to each generic point (cell) in the studied geographic area (Fig. 6); second, we must compute the accumulated cost coverage from point D1 (the other extreme) to each generic point in the same geographic area (Fig. 9); and, finally, the least expensive path from S1 to D1 passing through the generic point (cell) is obtained by adding the two accumulated costs coverages at this point.

The accumulated cost coverage from S1 and the accumulated cost coverage from D1 are shown in Figs. 6 and 9. As expected, we obtained the same least expensive path from S1 to D1 (darkest line in Fig. 6) and for D1 to S1 (darkest line in Fig. 9). The accumulated cost grew with the distance to the source for the S1-D1 path (Fig. 6) (from 0 in S1 to 596 742 € in D1) and for the D1-S1 path (Fig. 9) (from 0 in D1 to 596 742 € in S1). These results confirmed that the optimal path solution had been obtained and it was the only possible one because the cost of departure from the source was set to zero in both cases.

In order to compute the corridors from S1 to D1, first we added the value of the cell in the accumulated cost coverage from S1 and the value of the cell in the accumulated cost coverage from D1 for each cell in the geographic area. The cells with the same value in the resulting coverage (shown as D1-S1 corridor (€) in the legend of Fig. 10) define multiple noncrossing path lines from S1 to D1. For instance, the dark path that passes through point A has the value $h_{p_{S1},p_{D1}}(p_A) = 596\,742$€, which is the lowest cost path from S1 to D1 passing through point A. The path line passing through point D is another path solution with cost $h_{p_{S1},p_{D1}}(p_D) = 600\,373$ € (from S1 to D1 through point D).

The cost function (6) $h_{p_{S1},p_{D1}}(p_k)$ at each coverage point (cell) $p_k \in \Omega$ represents the total cost of a line route from S1 to D1 passing through p_k. The difference between this and the optimal cost path from S1 to D1 (in this example, 596 742 €) is the additional cost due to the path deviation from the optimal cost path.

The isolines shown in Fig. 10 define the corresponding boundaries (corridors) for different levels of $h_{\max}$. This Fig. 10 also shows that good path solutions are not necessarily following along contiguous areas.

For example, the dark path that passes through B is an example of an excellent path alternative to the one that passes through A since $h_{p_{S1},p_{D1}}(p_B) = 598\,946$€. All other possible alternatives between the two darkest paths in Fig. 10 (the path passing through point A and the path passing through point B) have higher costs.

The economic corridors show the path cost sensitivity to the characteristics of the terrain. The large uniform cost area near point C reflects indifference in path cost due to the uniformity of the geographic characteristics. Quite the opposite occurs near points E and F, which show a large influence of mountains on the path. The impact of uncertainties on the path can be understood by observing the shape of the corridors.

VI. CONCLUSION

The two main goals of this paper have been presented. The first one is a new methodology of automated optimal routing for new overhead electric power lines at the transmission and subtransmission levels that can be easily extended to the primary distribution level. The methodology is useful for the automated selection of the most economic route to build new lines. The second goal of the paper is the creation of power-line economic corridors. These corridors are feasible routing areas that link two particular points (origin and destination of the electric line) and keep associated line costs below a limit value determined by the planner; moreover, they also include multiple suitable economic routing alternatives for new power lines. The line costs considered are the operating, maintenance, and investment costs for a given electrical conductor size.

The GIS data format used in the proposed methodology is the raster format for input values (associated costs: terrain, slopes, obstacles, infrastructures, maintenance, etc.) as well as for computational results (minimum cost paths and economic corridors). Other innovate processes discussed in this paper are the inclusion in the new model of additional routing costs due to terrain slopes depending on the direction followed by the electric line; a new two-directional formulation from the origin to the destination for the economic corridor selection; and an original iterative DP optimization process.

Although this new methodology has been developed to build overhead electric power lines, it can be easily extended to other line routing problems, such as power underground distribution feeders, and takes advantage of the processing and viewing capabilities of GIS.

The mapping of economic line corridors is also an interesting tool to assess the costs of alternative routing paths. Different path solutions can be visually compared by observing the cost sensitivity to geographic factors and evaluating the uncertainties associated with routing costs.

Note that the proposed economic corridors can be selected as the starting point for advanced negotiation processes among different agents (utilities, local authorities, environmentalists groups, energy, or development agencies and others) who should reach a consensus on the best route to build new high-voltage overhead electric power lines (mainly transmission and/or subtransmission lines), which will be presented in a future paper.

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