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Routeing of power lines through least-cost path analysis and multicriteria evaluation to minimise environmental impacts

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ABSTRACT

Least-cost path analysis (LCPA) allows designers to find the "cheapest" way to connect two locations within a cost surface, which can be computed by combining multiple criteria, and therefore by accounting for different issues (environmental impact, economic investment, etc.). This procedure can be easily implemented with modern Geographic Information System (GIS) technologies, and consequently it has been widely employed to support planning and design of different types of linear infrastructures, ranging from roads to pipelines. This paper presents an approach based on the integration of multicriteria evaluation (MCE) and LCPA to identify the most suitable route for a 132 kV power line. Criteria such as cost, visibility, population density, and ecosystem naturalness were used for the analysis. Firstly, spatial MCE and LCPA were combined to generate cost surfaces, and to identify alternative paths. Subsequently, MCE was used to compare the alternatives, and rank them according to their overall suitability. Finally, a sensitivity analysis allowed the stability of the results to be tested and the most critical factors of the evaluation to be detected. The study found that small changes in the location of the power line start and end points can result in significantly different paths, and consequently impact levels. This suggested that planners should always consider alternative potential locations of terminals in order to identify the best path. Furthermore, it was shown that the use of different weight scenarios may help making the model adaptable to varying environmental and social contexts. The approach was tested on a real-world case study in north-eastern Italy.

1. Introduction

The increasing energy consumption and the connection of new neighbourhoods to the electric network call for power lines to be designed in a way that minimises potential effects on population health, preserves landscapes and reduces disturbance to wildlife. Power lines can have a significant impact on the environment during both the construction and the operation phases, due to factors such as electromagnetic pollution, forest clearing, habitat fragmentation, visibility of pylons (Söderman, 2006; Bailey et al., 2005; Bevanger and Broseth, 2004). For this reason, the insertion of long stretches of power lines in densely populated areas or fragile environments is an extremely complex issue. This is even more critical owing to the fact that the long-term effects of electromagnetic fields on human health are still largely unknown (ICNIRP, 1998; Repacholi, 1998; Valjus et al., 1995).

Techniques for the routeing of power lines and other linear infrastructures have evolved through the years, and today Geographic Information Systems (GIS) approaches allow designers to easily identify suitable land corridors. Among the available GIS-based techniques, least-cost path analysis (LCPA) is particularly useful to this purpose. LCPA allows the user to find the "cheapest" path from one point to another over a cost or friction surface. The cost surface is represented by a raster map in which each cell is given a cost that defines how "expensive" it is to pass through that cell. LCPA can be performed by generating an accumulated cost surface, on which a line can be identified that goes from a starting point to the destination (Douglas, 1994). The accumulated cost surface is generated from the cost surface, by calculating the cumulative cost of each cell from the starting point. The procedure is performed by an algorithm that searches, among the starting point's neighbouring cells, that with the lowest value. After selecting this cell, the algorithm iterates its procedure: the selected cell now becomes a starting point and its neighbouring cells are checked to identify the one with the lowest value. The least-cost path between any destination point and the pre-defined starting point is eventually found by moving backwards from the destination point over the accumulated cost surface, step by step, choosing cells at decreasing value (Lee and Stucky, 1998). After Dijkstra's (1959) several algorithms have been proposed for the implementation of LCPA in raster-based GIS (Stefanakis and Kavouras, 1995; Xu and Lathrop, 1995). The cost surface can be calculated by considering all criteria that affect the routeing of the linear infrastructure, and combining them

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through a multicriteria evaluation (Atkinson et al., 2005). The criteria should reflect the objectives the designers want to achieve in order to minimise impacts caused by the construction and the operation of the infrastructure.

Today, least-cost path analysis is a tool available in most commercial GIS, and it has been applied to a broad range of problems, the most common of which is probably infrastructure designing. Patrono and Saldana (1997) developed a script (ITC-ILWIS, 2001) to identify possible animal movement corridors. Balstrøm (2002) used ArcGIS to find the most time-saving routes for the inspection of rain gauges within a mountain region. Yusof and Baban (2004) used the IDRISI "Pathway" function (Eastman, 2003) to find the least-cost pipeline alignment between a town and a new tourist area in Malaysia. Yu et al. (2003) developed a method to roadway planning based on anisotropic accumulated cost surfaces that accounts also for the adoption of bridges and tunnels. Collishonn and Pilar (2000) proposed an algorithm for the definition of least-cost paths to be applied for the design of highways and canals that uses as an input the end points, the topography, the slope and cost. Feldman et al. (1996) used remotely sensed data and GIS analysis to perform a least-cost analysis for the routeing of pipelines. Several criteria were considered to evaluate the cost of passage (urban areas, geology, wetland, etc.), while remote sensing data were used to map land cover. The method was tested on a section of the Caspian oil pipeline. Georgia Transmission Corporation (2006) developed a standard siting method for overhead power lines based on three stages: the definition of a broad area, the identification of alternative corridors and the comparison of alignments within these corridors through LCPA.

This paper presents a method for routeing power lines to minimise their impacts on three main aspects: human health, landscape, and ecosystems. The approach presented here is a refinement of a method that has been applied and tested in real-cases. Therefore, the paper explores the boundary between theory and practice, discussing how the method can support the decision-making process. If compared to the existing studies on LCPA, the proposed approach introduces a significant novelty related to the location of power line start and end points. While these are commonly assumed to be fixed, we hypothesised that their position can vary within a small range around the expected location. This allows different paths to be obtained that may subsequently be compared through multicriteria evaluation (MCE). The study area is located in the Province of Rimini, in north-eastern Italy (Fig. 1). In this area, an existing 132 kV power line is to be removed and replaced by a new one. The area covers about 64 km^2 and extends on an east–west direction from the northern border of the Republic of San Marino to the Adriatic Sea. The geomorphology is characterized by flat areas in the north-eastern sector and low hills elsewhere with elevations ranging from 0 to 160 m. There are three main rivers crossing the area: the Ausa in the western part of the study area, and the Marano and Rio Melo in the central one. The whole area is densely populated, with one town (Riccione), some villages (Cerasolo, Ospedaletto, Sant'Andrea in Besanigo) and thousands of houses spread all over the territory. The land use is mainly characterized by cropland, orchards and vineyards, urban areas and industrial zones (Fig. 1).

2. Methods

2.1. Designing possible routes through LCPA

The LCPA algorithm is based on the definition of a so called cost surface, that is a raster map whose cells are assigned values

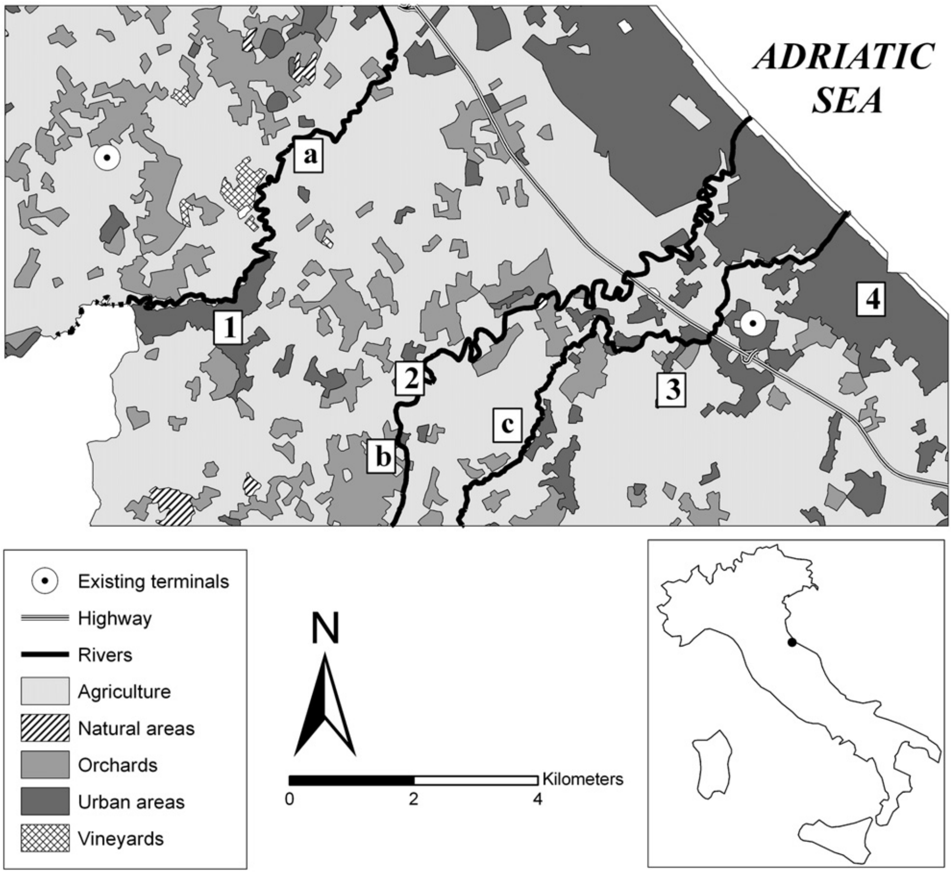

Fig. 1. Location of the study area and map of the main land uses. The urban areas of Cerasolo, Ospedaletto, Sant'Andrea in Besanigo and Riccione are indicated with numbers 1, 2, 3 and 4, respectively. The Ausa, Marano and Rio Melo rivers are indicated with letters a, b and c, respectively.

representing the "cost" for passing through them. This cost is not expected to be always of an economic kind: in this study, for example, it is related to the suitability of land to hosting a power line and it was assessed by considering the potential impact of such facility. Three main components were supposed to be potentially affected by a power line: human health, landscape and nature. Potential dangers to human health are mostly due to electromagnetic pollution, which is more intense near the facility. Landscape value can be significantly lowered by the power line if this crosses highly visible areas and/or is located in close proximity of cultural and recreational sites. Finally, power lines are likely to affect the naturalness of an area and to increase the risk of collision for birds (Bevanger and Broseth, 2004). These impacts were accounted for by considering the following criteria:

1. Human health:
    1.1. Density of building. It was adopted as a proxy for population density.
    1.2. Distance from buildings.
    1.3. Distance from sensitive buildings, such as hospitals and schools.
    1.4. Average height of buildings.
2. Landscape:
    2.1. Distance from highly valued cultural and recreational sites.
    2.2. Visibility from highly valued cultural and recreational sites, computed through Viewshed analysis (Burrough and McDonnell, 1998).
    2.3. Visibility from residential buildings.
3. Nature:
    3.1. Aspect. South-oriented slopes were considered to be critical areas because of a higher density of important bird species and the presence of upward currents.
    3.2. Distance from infrastructure corridors. In order to minimise habitat fragmentation, power lines should be built within a short distance from existing linear infrastructure corridors. Buffers were considered to this purpose (500 m for highways, 300 m for state and provincial roads, 100 m for power lines).
    3.3. Naturalness of the land cover. A 0–1 scale was used by assigning high values to natural vegetation cover (forest, woodland and shrubland), intermediate values to semi-natural cover (e.g., grassland) and low values to artificial cover (e.g., settlements).
    3.4. Ridges. The risk of bird collision is higher around ridges. Buffers around ridges were considered whose width is given by $L = h_{max}/2$, where h_{max} is the maximum elevation of the ridge.

Additionally, spatial constraints were applied in order to exclude from the analysis areas that are unsuitable to hosting a power line as assessed by the existing planning tools (areas of landscape/cultural interest identified by spatial plans at local and regional level, protected areas, areas affected by natural hazards, etc.) or legislations. The latter case refers in particular to areas around buildings: a 18-m buffer around each building was excluded from the analysis in order to comply with the quality objective on electromagnetic fields set by the Italian guidelines.

Eleven raster maps were generated, one for each of the criteria, through raster GIS operations. All GIS data were available at 1:10,000 scale. Aspect and visibility were assessed from the Digital Elevation Model. Maps were then made comparable to each other by reducing their values to a common 0–1 range (0 = low impact, 1 = high impact). This was done by means of value functions for continuous maps (e.g. distance from buildings) and by direct classification for discrete maps (e.g. naturalness). All maps were summed up on a cell-by-cell basis according to a weighted linear combination to provide the cost surface map. Weights were assigned by the experts involved in the analysis through direct assessment, and are presented in Table 1. The location of the source and destination points was not unique. Two sources and two destinations were identified within a 500 m-radius around the existing endpoints on areas not occupied by buildings, other infrastructures or anyway incompatible land uses. The LCPA was then run for all possible combinations between start and end points. To this purpose, the LCPA algorithm implemented in ArcGIS (ESRI, 2004) was employed. As a result, a number of least-cost paths was generated, each representing a potential route for the power line.

Table 1
Weights assigned to the criteria and sub-criteria maps during the design of possible power line routes.

Criteria	Weights for criteria	Sub-criteria	Weights for sub-criteria
Human health	0.62	1.1	0.30
		1.2	0.15
		1.3	0.15
		1.4	0.40
Landscape	0.19	2.1	0.10
		2.2	0.50
		2.3	0.40
Nature	0.19	3.1	0.15
		3.2	0.35
		3.3	0.35
		3.4	0.15

2.2. Comparing routes through MCE

The comparison and ranking of the paths were conducted by means of a set of additional criteria. Criteria included in this set differ from those previously employed to generate the cost surface map because they can be meaningfully assessed only with reference to already identified routes, rather than generally for the whole study area (Geneletti, 2010). These criteria included: habitat fragmentation, cost, human health and landscape. Habitat fragmentation caused by the different paths was computed by measuring the length of the path falling outside existing infrastructure corridors. The latter were seen as 40 m buffers around existing linear infrastructures. The cost was estimated by multiplying the length of a path by the expected average cost for a 132 kV power line (150,000 €/km). The impact on human health was estimated by counting the number of people living in areas where the intensity of the electromagnetic field is above the quality threshold for residential areas set by regional guidelines (0.2 μT). To this purpose a model was applied to evaluate at which distance from the power line the field intensity averages 0.2 μT and a buffer from the paths was generated accordingly. The number of people occurring into the buffer was extracted from census statistics of the Province of Rimini by considering the number of inhabitants of each cadastral unit and converting it into a people per building information. Finally, the visibility of each path was computed through the viewshed analysis implemented in IDRISI Kilimanjaro (Eastman, 2003). This allowed the estimation of the number of cells from which a given path is visible. Only the cells within 3000 m from the path were considered for this analysis. As a result, an evaluation matrix was built that included the performance scores of each path with respect to each of the four criteria. This evaluation matrix was used as input to a MCE aimed at ranking the potential power line paths. Such analysis was conducted with the decision support system DEFINITE 2.0 (Janssen et al., 2001).

In order to perform the MCE all values were standardised to a common range 0–1 by means of linear scale transformations. The interval standardisation method was selected, instead of the maximum standardisation method, for its ability to emphasise differences among alternatives by stretching values between 0 and 1 (Geneletti, 2005). This is actually helpful in case the original differences are not particularly significant. The equation of the interval method is as follows:

$$1 - \frac{\text{score} - \text{lowest score}}{\text{highest score} - \text{lowest score}} \quad (1)$$

Table 2
Weight sets applied to compare the power line routes according to the neutral (NP), economic (EP), health (HP), and socio-economic (SP) perspective.

	NP	EP	HP	SP
Length (m)	0.25	0.55	0.15	0.30
People	0.25	0.15	0.55	0.30
Visibility	0.25	0.15	0.15	0.20
Fragmentation (m)	0.25	0.15	0.15	0.20

Four sets of weights were considered in order to account for different decision-making perspectives and enhance the applicability of the method to different contexts:

- Neutral perspective (NP): equal weights for all criteria
- Economic perspective (EP): highest weight to the economic criterion;
- Human health perspective (HP): highest weights to the human health criterion;
- Socio-economic perspective (SP): highest weights to economic and human health issues.

Weights were directly assigned by the experts involved in the assessment and are reported in Table 2. Weighted linear combination was used to combine the criteria and get a final score for each path. A sensitivity analysis was performed to assess the robustness of the results when criterion scores are affected by uncertainty. The uncertainty on scores was simulated by means of a number generator to obtain 2000 random numbers uniformly distributed within a 25% uncertainty range around each original score. The MCE evaluation was then repeated 2000 times, and the results summarised in a frequency table, reporting how many times each path ranked in each position.

Table 3
Evaluation matrix showing the performance score of each path against the four criteria selected for the comparison.

	Lcp_11	Lcp_12	Lcp_21	Lcp_22
Cost (1000 €)	1804.2	1990.5	1792.0	1978.6
Human health (number of people)	129	121	130	122
Visibility (number of cells)	23,129	24,486	23,144	24,501
Fragmentation (m)	10,654	10,895	10,479	10,719

3. Results

Four paths (Lcp_11, Lcp_12, Lcp_21 and Lcp_22) were obtained as shown in Fig. 2. These differ from each other only partly in that Lcp_11 and Lcp_12 share the first section, and so do Lcp_21 and Lcp_22. Lcp_11 and Lcp_21 share the last section, and so do Lcp_12 and Lcp_22. Their overall length is about 12 km, of which 6.7 km are common to all of them. Differences among paths are more extended on the eastern side than on the western one. Approaching the destination nearby Riccione, Lcp_11 and Lcp_12 move to northeast passing through arable lands and urban green areas, whereas Lcp_12 and Lcp_22 move to southeast crossing arable lands, orchards, vineyards and industrial areas. All paths skip the major villages within the study area (Cerasolo, Ospedaletto and S. Andrea in Besanigo) where impacts on human health would be particularly intense due to high population densities. All paths cross the highway, but Lcp_12 and Lcp_22 do it in correspondence of a large junction.

The evaluation matrix, which reports the performance of each alternative path against the four criteria used for their comparison, is presented in Table 3. The scores differ very little and this is in favour of using the interval standardisation method. The multicriteria comparison

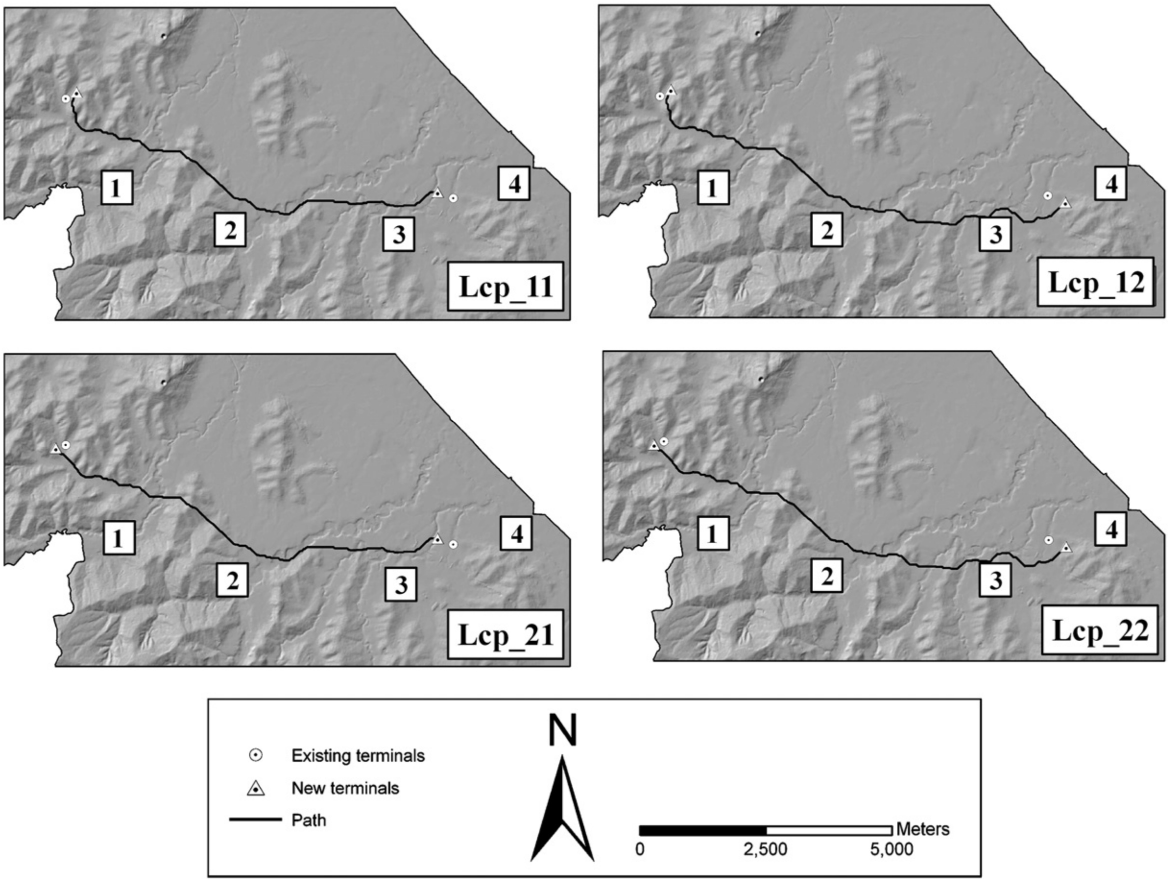

Fig. 2. The four least-cost paths superimposed to a Digital Elevation Model (DEM) of the study area. The urban areas of Cerasolo, Ospedaletto, Sant'Andrea in Besanigo and Riccione are indicated with numbers 1, 2, 3 and 4, respectively.

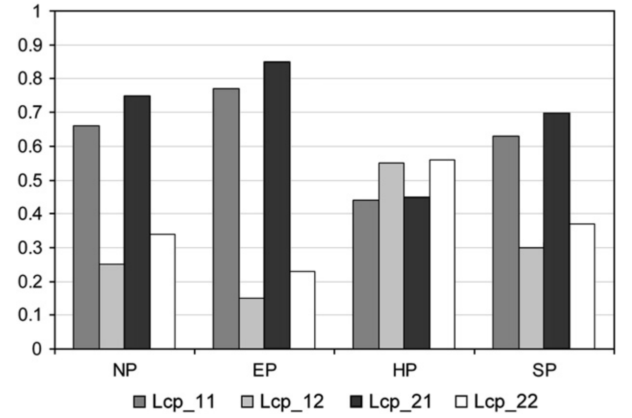

Fig. 3. Rankings of the four paths according to the neutral (NP), economic (EP), health (HP), and socio-economic (SP) perspective.

provided a clear result: Lcp_21 and Lcp_11 ranked first and second respectively under the neutral, economic and socio-economic perspective (Fig. 3). On the contrary, they ranked third and four under the human health perspective, when Lcp_22 and Lcp_12 occupied the first and second position, respectively. A significant performance gap was always observed between the first two alternatives and the remaining ones, though this difference is smaller under the human health perspective. The sensitivity analysis underlined the significant stability of the rankings with respect to variation in the criterion scores for the neutral, economic and socio-economic perspectives (Table 4). More variability characterized the human health perspective, where the first two positions of the rankings assigned with similar frequencies to Lcp_22 and Lcp_12, and the last two positions assigned to Lcp_11 and Lcp_21.

4. Discussion and conclusions

Least-cost path analysis is particularly interesting for the routeing of power lines, because it is a fast and replicable process that allows the user to integrate information from different sources. Although such analysis is usually performed starting from pre-defined start and end points, this study showed how to obtain multiple paths and to compare them in a multicriteria fashion. The exercise, applied to a 12 km power line showed that a mere 500 m variation of the path's start and end points may significantly affect the path itself. This means that slightly varying the locations of these points would allow new and possibly less harmful paths to be identified. This feature is particularly relevant when decision-makers are given freedom for the design of a new line. However, it is often the case in real practice (and particularly in densely built-up areas) that the location of end-stations is fixed. Nevertheless, the proposed approach can offer advantages even in these situations if one thinks of considering alternative end-stations in the surrounding of the original ones, generating the related least-cost paths, identifying the most suitable one, and eventually linking its end-stations to the original ones via underground connection. By doing so, the decision-maker could design a power line that would have never been identified with conventional LCPA.

Table 4
Frequency matrix obtained after applying a 25%-uncertainty range on the scores. The matrix shows how many times (in %) each path ranked in each position.

	1st	2nd	3rd	4th
Neutral perspective (NP)				
Lcp_21	0.72	0.28	0.00	0.00
Lcp_11	0.28	0.72	0.00	0.00
Lcp_22	0.00	0.00	1.00	0.00
Lcp_12	0.00	0.00	0.00	1.00
Economic perspective (EP)				
Lcp_21	0.68	0.32	0.00	0.00
Lcp_11	0.32	0.68	0.00	0.00
Lcp_22	0.00	0.00	1.00	0.00
Lcp_12	0.00	0.00	0.00	1.00
Human health perspective (HP)				
Lcp_22	0.51	0.45	0.05	0.00
Lcp_12	0.44	0.50	0.06	0.00
Lcp_11	0.06	0.06	0.48	0.41
Lcp_21	0.00	0.00	0.41	0.59
Socio-economic perspective (SP)				
Lcp_21	0.68	0.32	0.00	0.00
Lcp_11	0.32	0.68	0.00	0.00
Lcp_22	0.00	0.00	0.99	0.01
Lcp_12	0.00	0.00	0.01	0.99

The use of different evaluation perspectives in the comparison phase is useful to adapt the process to different contexts. The human health perspective, for example, might be a good choice for routeing in densely populated regions, where the potential impact on people would be particularly high (as it happened in this particular case). On the other hand, an economic perspective would likely supply a good answer when few environmental constraints exist, and the overall cost is the main issue to account for. For instance, this method was applied, within the same study, also to a study area in Tuscany (Italy), where environmental constraints were tighter (e.g. forest clearing along the pre-existing power line) and the urbanization was less intense. In that case, the nature/landscape oriented perspective worked better.

This study was commissioned by the company in charge of managing the electrical network, and was carried out as a contribution to the first part of the Environmental Impact Statement (EIS), where possible alternatives for the power line project were to be discussed and compared. In the second part of the EIS, the blueprint of the selected project was used to predict and assess in detail its environmental impacts. Although the study presented here relied on a GIS data set already available that had been compiled by the regional authority, the detailed assessment required further data collection and reprocessing. The next step of the approach, currently in drafting, consists in upscaling the method to support the Strategic Environmental Assessment (SEA) of Electrical network development plans. Such plans are drawn by the same managing company, and aimed at identifying primary corridors for the extension of the power line network. The scale of such plans is national, hence the detail of the analysis will change, and will target the identification of wider corridors, rather than actual paths for the power lines. Approaches based on LCPA have been applied in landscape ecology to support the identification of corridors for animal movement (Pinto and Keitt, 2009), and will be adapted to the case of power line. The identification of corridors will allow to delineate boundaries within which more detailed data will be collected, such as high resolution aerial photography and land tenure records.This is to support the generation and comparison of possible routes.

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References

Atkinson DM, Deadman P, Dudycha D, Traynor S. Multi-criteria evaluation and least cost path analysis for an arctic all-weather road. Appl Geogr 2005;25:287–307.

Bailey K, Grossardt T, Jewell W. Participatory routing of electric power transmission lines using the EP-AMIS/GIS multicriteria evaluation methodology. Proceedings of 10th International Conference on Communication & Information Technologies

(ICT) in Urban Planning and Spatial Development and Impacts of ICT on Physical Space; 2005.

Balstrøm T. On identifying the most time-saving walking route in a trackless mountainous terrain. Dan J Geogr 2002;102:51–8.

Bevanger K, Broseth H. Impact of power lines on bird mortality in a subalpine area. Anim Biodivers Conserv 2004;27(2):67–77.

Burrough PA, McDonnell RA. Principles of Geographic Information Systems. Oxford Univ Press; 1998.

Collishonn W, Pilar JV. A direction dependent least-cost-path algorithm for roads and canals. Int J Geogr Inf Sci 2000;14(4):397–406.

Dijkstra EW. A note on two problems in connexion with graphs. Numer Math 1959;1: 269–71.

Douglas DH. Least cost path in GIS using an accumulated cost surface and slope lines. Cartographica 1994;31(3):37–51.

Eastman JR. IDRISI Kilimanjaro Guide to GIS and Image Processing. Clark University, Worcester, MA, USA: Clark Labs; 2003.

ESRI. What is ArcGIS? (9.x version) Redlands. CA, USA: ESRI Press; 2004.

Feldman SC, Pelletier RE, Walser E, Smoot JC, Ahl D. GIS, remote sensing analysis used to select potential route. Pipe Line Gas Ind 1996:52–5.

Georgia Transmission Corporation. EPRI-GTC Overhead Electric Transmission Line Siting Methodology; 2006.

Geneletti D. Multicriteria analysis to compare the impact of alternative road corridors. A case study in northern Italy. Impact Assess Proj Appraisal 2005;23(2):135–46.

Geneletti D. Combining stakeholder analysis and spatial multicriteria evaluation to select and rank inert landfill sites. Waste Management. Waste Manage 2010;30: 328–37.

International Commission on Non-Ionizing Radiation Protection. Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz); 1998.

ITC. ILWIS 3.0 Academic User's Guide. Enschede, The Netherlands: International Institute for Aerospace Survey and Earth Sciences; 2001.

Janssen R, van Herwijnen M, Beinat E. DEFINITE. Case studies and user manual. Institute for Environmental Studies, Vrije Universiteit Amsterdam, R-01/01; 2001.

Lee J, Stucky D. On applying viewshed analysis for determining least-cost paths on Digital Elevation Models. Int J Geogr Inf Sci 1998;12(8):891–905.

Patrono A, Saldana A. Modeling with neighbourhood operators. ILWIS 2.1 Application Guide, ITC, Enschede; 1997.

Pinto N, Keitt TH. Beyond the least-cost path: evaluating corridor redundancy using a graph-theoretic approach. Landscape Ecol 2009;24:253–66.

Repacholi MH. Low level exposure to radiofrequency fields: health effects and research needs. Bioelectromagnetics 1998;19:1-19.

Söderman T. Treatment of biodiversity issues in impact assessment of electricity power transmission lines: a Finnish case review. Environ Impact Assess Rev 2006;26: 319–38.

Stefanakis E, Kavouras M. On the determination of the optimum path in space. Proceedings of the European Conference on Spatial Information Theory, COSIT95, Lecture Notes on Computer Science. Berlin: Springer; 1995. p. 241–57.

Valjus J, Hongisto M, Verkasalo P, Jarvinen P, Heikkila K, Koskenvuo M. Residential exposure to magnetic fields generated by 110–400 kV power lines in Finland. Bioelectromagnetics 1995;16:365–76.

Xu J, Lathrop RG. Improving simulation accuracy of spread phenomena in a raster-based Geographic Information System. Int J Geogr Inf Sci 1995;9:153–68.

Yu C, Lee J, Munro Stasiuk MJ. Extensions of least-cost path algorithms for roadway planning. Int J Geogr Inf Sci 2003;17(4):361–76.

Yusof KW, Baban S. Least-cost pipeline path to the Langkawi Island, Malaysia using a geographical information system (GIS). Proceedings of Map India Conference 2004; 2004. Available online at http://www.gisdevelopment.net/application/Utility/others/pdf/mi04053.pdf.