IET Generation, Transmission & Distribution

Research Article

ISSN 1751-8687
Received on 18th July 2016
Accepted on 19th August 2016
doi: 10.1049/iet-gtd.2016.1119
www.ietdl.org

Least-cost path analysis and multi-criteria assessment for routing electricity transmission lines

Rodolfo Mendes de Lima[1,2] ✉, *Reinis Osis*[2,3], *Anderson Rodrigo de Queiroz*[4], *Afonso Henriques Moreira Santos*[1,2]

[1] *Federal University of Itajubá – UNIFEI, Itajubá, MG, Brazil*
[2] *iX Estudos e Projetos Ltda., 341 Joaquim Francisco Street, Varginha, Itajubá, MG, Brazil*
[3] *Espaces et Sociétés (ESO) – UMR CNRS no. 6590, Avenue Oliver Messiaen, University of Maine, France*
[4] *Department of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, NC, USA*
✉ *E-mail: rodolfo.mendes.lima@gmail.com*

Abstract: The classical approach for transmission line (TL) routing based on paper maps, aerial photographs and field visits can generate inconsistent results, besides being a time consuming and intensive labour activity. The application of methodologies based on geographic information system (GIS) combined with multi-criteria assessment (MCA) methods can generate time and cost savings on the planning step. However, this methodology still must be better assessed for its applicability and improvements can be made. Therefore, this study aims at verifying the applicability of a GIS methodology for TL routing using analytic hierarchy process (AHP) for weighting criteria. In addition, the effectiveness of AHP method is evaluated comparing the previously attained results with a route modelled using monetary values to weight the criteria. To achieve the objectives, the methodology is applied for an area in the northern region of Brazil (state of Pará) where a 230 kV TL is already implemented: the TL Vila do Conde-Castanhal. As a result, routes with lower length and lower total cost than the implemented TL were obtained, which suggest the potential benefits of applying the proposed methodology compared with traditional route planning, which does not use quantitative MCA and more advanced GIS tools.

1 Introduction

Routing is the initial stage of the planning process of transmission lines (TLs), where the designer decides the best areas to cross, considering existing restrictions. Technically speaking, the best TL route is the simplest one, with as few of deflection angles as possible, because changes in direction require sturdier structures to support additional loads. However, the designer should consider other aspects as compensation costs, environmental and social issues, obstacles as bridges, rivers, lakes, urban areas and so on, when defining an optimum route. This process can be defined as an optimisation problem wherein the main objective is to minimise installation and maintenance costs, influenced by strictly technical and geographically depending aspects as accessibility, environment, terrain complexity (slope and relief), geotechnical characteristics of soil, land use (urban areas, forests, agricultural areas etc.) and existing infrastructures among others [1, 2].

The manual TL routing is a time consuming and intensive labour activity, which requires a large amount of detailed information and experienced design engineers [1]. Moreover, the classical approach based on paper maps, aerial photographs and field visits can generate inconsistent results, which may lead to the need to redesign projects and delays [3]. Therefore, taking into account the complexities of TL route planning process and its strong relation with geographical features, the use of geographic information system (GIS) combined with multi-criteria assessment (MCA) methods can generate time and cost savings for the planning process. Husain *et al.* [4] said that the electric industry in the USA has responded with many initiatives to optimise the TL planning, including GIS-based system. According to [5], in engineering problems related to path finding or site placing, GIS is the most powerful tool. Also, for problems involving many criteria such as routing TLs, MCA methods like the analytic hierarchy process (AHP) should be used to make the most accurate decision.

Methodologies for route optimisation based on GIS systems are applied in many areas: identification of wildlife routes [6]; trails tracing optimisation in dune forest [7]; archaeology, on studies about dispersal of human ancestors [8], determination of road paths [9]; among other applications. For TLs, most studies about route optimisation consider only aspects that are geographically dependent such as land use, geology, utility infrastructures, rivers, environmental protection areas, among others [4, 5, 10, 11]. However, it is important to consider strictly technical aspects such as in [1], which describes a TL route optimisation using GIS and dynamic programming. The authors, besides geographical aspects, also considered incremental costs related to changes in the direction of the route that demand special towers to support additional loads. On the other hand, some studies are more specific as in [12], which presents a TL route methodology through least-cost path and MCA tools in a region in northern Italy to reduce environmental impacts, or in [13], which presents a TL route optimisation based on lightning incidence.

Generally, to weight the criteria, a MCA method as AHP is used [3–5, 9–12], although the effectiveness of these methods to determine the weight of each criterion for TL routing still needs to be better understood. Yildirim and Nisanci [11], in a TL routing study in Turkey, compared a modelled TL with an already installed TL in relation to the length and the affected area regarding some land uses and particularities. The modelled route presented a greater length, but it crossed a smaller area of social and environmental importance and the authors did not compare the routes in relation to technical and economic aspects. Dedemen [10] compared four routes generated by use of GIS and MCA in relation to the final costs, where each route was generated according to the assessment of a decision maker. However, the final costs were determined only to compare the routes and were not included in the route optimisation process and the modelled routes were not compared with the already implemented TL in the study area. It is also possible to assign monetary values to the criteria [1], which address the route optimisation more realistically. Nevertheless, there are difficulties to determine the costs related to each criterion, involving exhaustive searches on databases, as well as technical knowledge about the components of the TL.

Considering the studies about route TLs using GIS and MCA methods presented in the literature, the methodology proposed in this work aims at better assessing the characteristics of the problem at hand and exploring other important aspects that were not previously incorporated, creating a better decision-making framework. For this, it is important to consider economic and technical aspects together with geographical, environmental and social aspects for the route optimisation. Also, the effectiveness of the MCA method needs to be better evaluated.

The main objective of this paper is to verify the applicability of a methodology for TL route optimisation based on GIS and AHP, considering technical and economic aspects along with geographical, environmental and social aspects. Moreover, a specific objective is defined: the assessment whether the AHP method for weighing criteria is effective, by comparing a route modelled by using AHP weights with a route modelled by using monetary values as weights for the criteria. To achieve these goals, the methodology is applied to an area in the northern region of Brazil (state of Pará) where a 230 kV TL is already implemented, TL Vila do Conde-Castanhal. In addition, the modelled routes are compared with the existing TL in order to compare the proposed methodology with the traditional method of route selection.

The main motivation for this work is the expansion of the power transmission sector. It is estimated that Brazil has 20,018 km of TLs to be implemented and an increase of 60 new substations between 2015 and 2020. This expansion results in about US$ 92 billion in TLs and US$ 22 billion in substations [14]. In the USA, the investment costs of transmission planned for the period of 2015–2018 is approximately US$ 85 billion [15]. In addition, the selection of the study area was supported by particularities of the northern region of Brazil, mainly the environmental restrictions, large rivers to transpose and large lengths of TLs to connect the generation plants to the electric power system, which add difficulties to the planning process.

The paper is structured as follows: Section 2 presents the methodology proposed and the theoretical aspects; Section 3 presents the application of the methodology for study area; Section 4 shows the results, as well as the comparison with other similar studies; finally, Section 5 presents remarks and the conclusions.

2 Integrating GIS and AHP for the least-cost path definition

The methodology proposed (Fig. 1) can be divided into two main stages: (i) generation of a cost surface that incorporates several criteria, weighted and integrated by applying the AHP method and map algebra; (ii) determination of the least-cost path using the Dijkstra's algorithm. The next topics of this section present details and theoretical aspects of such methodology.

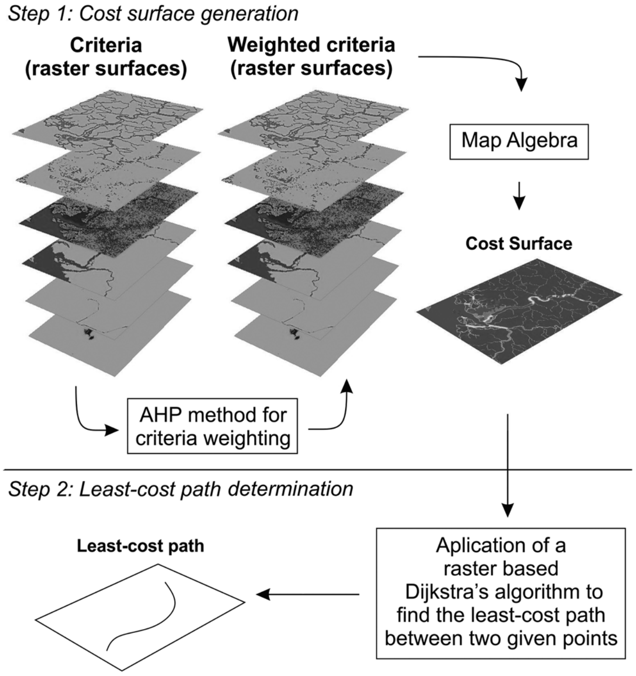

Fig. 1 *Chart of proposed methodology*

2.1 Cost surface generation

Most of the work presented in the literature that employs GIS tools for route optimisation is based on the concept of 'cost surface', defined as a raster file type, where the values associated to each pixel are used as weights to calculate the least-cost path between two points [1, 3–13, 16, 17]. Raster type files are formed by a pixel matrix (or cells) with defined dimensions. Each pixel has a unique numeric value representing a condition of the area covered by that cell. For example, the topography of a given region can be represented by a raster file, where each pixel has a value corresponding to an average quota for the area covered by that pixel. The size of the pixels is called spatial resolution and indicates the length of the edge of the pixels. The weights represent the resistance, friction or crossing restriction pixels, and can express monetary cost, time, distance, risk or other aspects, depending on the application [16]. The cost surface can include many criteria, weighted and integrated by applying a MCA method and map algebra [18], wherein map layers are processed by operations that are cartographic in nature. In this work, the map algebra operations were made by using tools of QGIS 2.6.0. Details about these tools and proceedings are presented in Section 3, where the study case is described.

It is important to highlight that the main criteria for routing a TL are determined according to the purpose of the study. In [12], the authors used 11 criteria: density of building, distance from buildings, distance from sensitive buildings, such as hospitals and schools, average height of buildings, distance from highly valued cultural and recreational sites, visibility from highly valued cultural and recreational sites, visibility from residential buildings, aspect, distance from infrastructure corridors, naturalness of the land cover and ridges. Regarding the economic aspects, in [1] the authors highlighted four sets of components that influence implementation and maintenance costs: equipment costs – regardless of geographic features; slope costs, associated with the local slope of the terrain; direction change costs; and geographic factors, which are: (i) accessibility costs: represented by the costs of equipment transportation, installation and maintenance, depending on the quality and type of the existing access routes in a studied area and the need for opening new access routes in case of new TLs; (ii) costs due to specific geographic characteristics of the area: compensation and expropriation costs associated with land use; costs of tower foundations according to soil type; costs associated with vegetation, for example, need for higher towers to cross forested areas with significant ecological importance, vegetation suppression and/or pruning costs; additional maintenance costs in areas susceptible to corrosion near the coast; additional costs for areas of high environmental importance; (iii) terrain complexity: slope and relief complexity influence on determining the types and heights of the towers, where flatter lands are more favourable; (iv) costs due to obstacles: roads, railways, rivers and existing TLs. The crossing of these elements requires reinforced structures or even the use of underground lines. The need of signalling equipment, due to the proximity of certain infrastructure such as airports, may also be implemented.

2.2 MCA method: AHP

The AHP is a multiple criteria decision-making tool, which can be used to measure the relative dominance or preference of elements related to a main objective [19]. The main advantage of AHP,

Table 1 Example of paired comparison matrix regarding four criteria

	Soil	Vegetation	Urban area	Relief
soil	1	1/3	5	1
vegetation	3	1	5	1
urban area	1/5	1/5	1	1/5
relief	1	1	5	1

compared with other MCA methods (ELECTRE and simple additive weighting), is that the importance of each element (criterion) is determined by using paired comparisons generating better results. This can be useful for weighing criteria in route optimisation, which can be verified in [3–5, 9, 10].

The paired comparisons are made by using a paired comparison matrix (Table 1), wherein each element is compared with all others according to their importance. For example, Table 1 shows the 'soil' criterion compared with other criteria. In line 1, the soil criterion is rated as moderate less important than the criterion 'vegetation', and strongly more important than the criterion 'urban area', and equally important as the criterion 'relief'. The other lines demonstrate the valuation of the other criteria. Comparisons can be carried out by actual measurements or by means of a preference scale (Table 2) that reflects the relative importance of the decision-maker's preferences and perceptions. The effectiveness of the preference scale was evaluated by applications with a large number of people and by theoretical comparisons with other scales [19]. Criteria weights are determined based on the paired comparison matrix and some methods can be used for such task: the least squares method, the logarithmic least squares method and the eigenvector method [20]. In this work, a spreadsheet developed by Goepel [21] is used for the application of AHP method, wherein the weights are automatically obtained, based on the logarithmic least squares method.

2.3 Least-cost path using Dijkstra's algorithm

Given a directed graph (V, A), where V is the set of nodes and A the set of edges with source node s, sink node t and weight w_{ij} for each edge (i, j) in A, consider the following mathematical model

$$W_{\text{total}} = \min_{x_{ij}} \sum_{ij \in A} w_{ij} x_{ij} \tag{1}$$

$$\text{s.t.} \ \sum_j x_{sj} - \sum_j x_{js} = 1 \tag{2}$$

$$\sum_j x_{tj} - \sum_j x_{jt} = -1 \tag{3}$$

$$\sum_j x_{ij} - \sum_j x_{ji} = 0, \qquad \forall i \in \frac{V}{\{s, t\}} \tag{4}$$

$$x_{ij} \geq 0, \quad \forall ij \in A \tag{5}$$

Table 2 Fundamental scale for paired comparisons [19]

Importance	Definition
1	equal importance: both criteria influence the objective equally
3	moderate importance: experience and judgement moderately favour one criterion over another
5	strongly importance: experience and judgement strongly favour one criterion over another
7	very strong importance: criterion strongly favoured and its domination is demonstrated on practice
9	extreme importance: evidence favouring one criterion over the other has got the highest possible validity
2, 4, 6 and 8	intermediate values

Decision variables x_{ij} indicate whether an edge (i, j) is part of the shortest path ($x_{ij} = 1$) or not ($x_{ij} = 0$). The goal is to select the set of edges that form the minimal total weight to go from source node s to sink node t. The model is subject to structural constraints, which require for all vertices (except the source and the sink nodes) that the number of incoming and outgoing edges that are part of the path must be the same forming a path from s to t. Equation (2) requires that only one edge is active going from s to an adjacent edge, (4) requires that only one edge reaches the sink, (5) requires that at most one edge is active between nodes i and j and (5) provides non-negativity for decision variables. Special properties of this least-cost path formulation such as integral values for decision variables are discussed in [22].

The most widely used algorithm to solve the shortest path problem is the Dijkstra [13]. This algorithm was originally developed to solve two problems in a weighted and directed graph of n nodes, for the case in which all edge weights are non-negative: (i) constructing a tree with minimum total weight from each node n to a given source node s. The term 'tree' is defined as a graph with only one path between two nodes; (ii) finding the path of least weight between two given nodes from the tree of minimal total weights [23]. Considering the graph (V, A) presented above, for the case in which all edge weights w_{ij} are non-negative, the implementation of the Dijkstra's algorithm is shown in Fig. 2 [24].

The notation used to represent attributes of nodes was $n.d$ for an attribute d of a node n. Thus, for each node $i \in V$ the algorithm maintains a shortest-path estimate $i.d$, which is an upper bound on the weight of a shortest path from source node s to i. Initially for all nodes i, $i.d = \infty$, and for the source node s, $s.d = 0$. The algorithm maintains a set of nodes S whose final shortest path weights from source s have already been determined. The algorithm repeatedly extracts node $j \in Q$ with the minimum-shortest path estimate $j.d$, adds j to S and relaxes all edges leaving j. Details about this implementation of the Dijkstra's algorithm can be found in [24]. At the last iteration, the set S represents the Dijkstra's tree with the shortest paths from each node to source node s.

To employ this algorithm in a raster-based GIS, a virtual network can be constructed considering the centres of each raster cell as nodes and the connections between the neighbour cells as edges of the graph [17]. Then, the weight (cost) to go from node i to node j (Fig. 3) is represented in the models (1)–(5) by w_{ij} and are computed using the following equations

$$w_{ij} = \frac{c_i + c_j}{2}, \quad \forall ij \in A^{\mathrm{N}} \tag{6}$$

$$w_{ij} = \sqrt{2}\frac{c_i + c_j}{2}, \quad \forall ij \in A^{\mathrm{D}}. \tag{7}$$

where A^{N} is the subset of the set of arcs that represents the direct neighbours of node i, A^{D} is the subset of the set of arcs that

```
Algorithm
for each node $i \in V$
    $i.d = \infty$
$s.d = 0$
$S = \emptyset$
$Q = V$
while $Q \neq \emptyset$
    $j$ = the nodes in $Q$ with the minimum $'d'$ value
    $Q = Q - \{j\}$
    $S = S \cup \{j\}$
    for each node $i \in$ {neighbours of $j$}
        if $i.d > j.d + w_{ij}$
            $i.d = j.d + w_{ij}$
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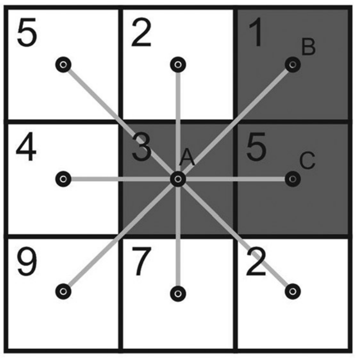
Fig. 2 *Dijkstra's algorithm*



Crossing cost (A to B) = 1,4142(3+1)/2=2,8284
Crossing cost (A to C) = (3+5)/2 = 4,0000

Fig. 3 *Example of neighbourhood between pixels and calculation of the weight of the edges*

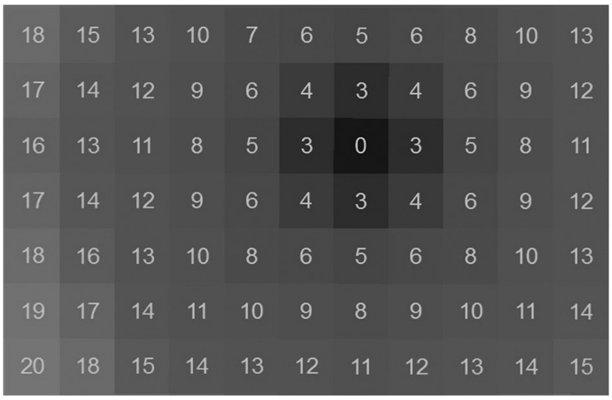
represent the diagonal neighbours of node *i* and c_i and c_j are the cost values of the neighbouring pixels, which for the purpose of this work is represented by a combination of different attributes as described in Section 3.1.

The Dijkstra's tree for a raster-based GIS methodology is represented by a raster file designated as accumulated cost surface [17] that stores the accumulated costs of the lowest cost route to a source cell (Fig. 4). The least-cost path from any point of this surface can be found only by searching the neighbouring pixel with the shortest accumulated weight towards the source point. In this work, the accumulated cost surface and the least-cost path are generated by using tools of QGIS 2.6.0. The details about the proceedings and those tools are presented in the next section, which describes the case study.

3 Case study: application of GIS-MCA methodology for economic route optimisation of a 230 kV TL in Brazil

The application of GIS-MCA methodology proposed in this work can be divided into four stages: (i) identification, acquisition and pre-processing of spatial data related to the criteria that influence the costs of implementing a TL; (ii) weighting of criteria using AHP and determination of costs (monetary values) related to each criterion; (iii) integration of criteria through application of map algebra, resulting in two cost surfaces: one using the criteria weighted by AHP and another one by assigning monetary values to the criteria; (iv) application of least-cost path tools to obtain the optimised routes.

The software used for all treatments and processing of spatial data was the QGIS 2.6.0.



18	15	13	10	7	6	5	6	8	10	13
17	14	12	9	6	4	3	4	6	9	12
16	13	11	8	5	3	0	3	5	8	11
17	14	12	9	6	4	3	4	6	9	12
18	16	13	10	8	6	5	6	8	10	13
19	17	14	11	10	9	8	9	10	11	14
20	18	15	14	13	12	11	12	13	14	15

Fig. 4 *Representation of a hypothetical cost-accumulated surface*

A region in the state of Pará, Brazil, between the coordinates 1° 10′–1°45′S and 47°40′–48°50′W is used as a pilot area, where there is a 230 kV TL located between Vila do Conde and Castanhal substations [25]. The application of the methodology allowed the comparison between the routes generated by the proposed methodology and the existing TL. Fig. 5 presents the location of the TL.

3.1 Selected criteria

The selection of criteria is performed considering two main aspects: (i) structural costs and (ii) additional costs related to the geographical aspects of the study area. This approach is similar to the one proposed by Monteiro *et al.* [1], wherein the authors set equipment costs, regardless of geographic features, and costs related to geographical features. The equipment costs refer to the material costs of a TL implementation, considering ideal conditions: a TL crossing flat places without any restriction, such as rivers, urban areas, conservation areas, among others. Therefore, a criterion is considered for this aspect: the 'structures' criterion, which assumes a single value for the entire study area.

The additional costs comprise the difference between the costs of the crossing of a geographical feature (e.g. an urban area or a forest) in relation to the structural costs. This aspect is the basis of the cost surface, since it will determine the cost differences in the two-dimensional space of search for the least-cost path tools. The geographical criteria are determined considering the main characteristics of the study area and eight spatial criteria with significant importance in determining the TL route were identified: airports, wetlands, permanent preservation areas (PPAs), hydrography, navigable rivers, Brazilian interconnected power system (BIPS), conservation units (CUs) and land use (Fig. 6 and Table 3). It is important to highlight that the criteria were selected with the support of experts in TL planning and projects, which ensured the effectiveness and all-inclusiveness of criteria, considering the characteristics and particularities of study area, as well as the technical attributes of a 230 kV TL. The independency of criteria was also ensured. Although the 'navigable rivers' criterion is derived from the 'hydrography' criterion, they are independent because 'navigable rivers' have costs associated with the height of the towers and the 'hydrography' is associated with the need of special structures to cross wide stretches, whether the stretches are navigable or not. The geographical features for each criterion were obtained by accessing data from public agencies. All spatial files were standardised for projection system UTM zone 22S and datum WGS84.

3.2 Weighting of the criteria

As mentioned before, for weighting the criteria by the AHP methodology, an automatic spreadsheet calculation developed by Goepel [21] was used. In order to ensure a proper weighting of the criteria, an expert in TL projects was consulted and the AHP method was applied according to the judgements of this expert.

The costs related to each criterion (monetary values in US$/km) are determined based on a database, provided by the Brazilian Electricity Regulatory Agency (ANEEL) [33]. The technical features and each component of the TL Vila do Conde-Castanhal are considered [25]. The costs are originally obtained in Real (Brazilian currency) and converted to US Dollar considering exchange rates of April 2015. The assessed costs do not represent the total costs of implementing a TL, but only the structures implementation costs (material and labour), clean-up costs of the ground under TL, compensation costs and environmental costs. Costs of engineering projects and creating access routes are not considered to simplify the method application.

3.3 Obtaining cost surfaces and defining optimised routes

The criteria are all standardised to vector files, specifically in shapefile format (*.shp). This file type allows the storage of multiple attributes. This makes it possible to store the weight data

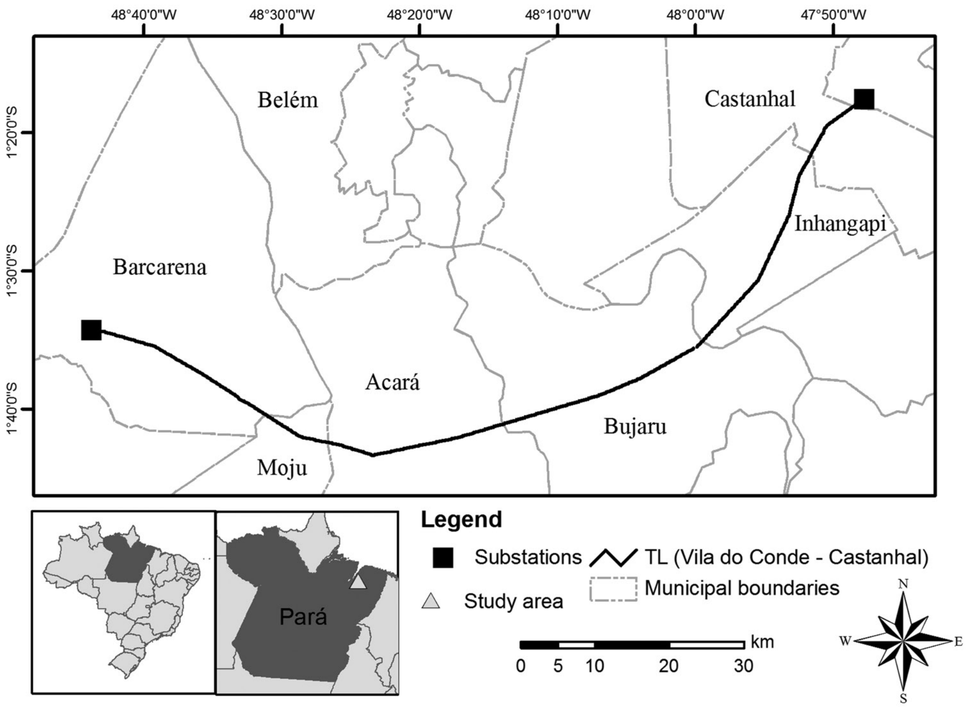


Fig. 5 *Spatial location of TL Vila do Conde-Castanhal*

(costs and AHP weights) associated with geographic features for each criterion in only one file. Based on the shapefile for each criterion two files in raster format (*.tif) are generated: one with monetary values and another with the weights obtained applying the AHP. A pixel size of 90 m is adopted for the raster files, which corresponds to the scale of the information used. Finally, two cost surfaces are obtained by summing up the raster files and the value of the structures criterion.

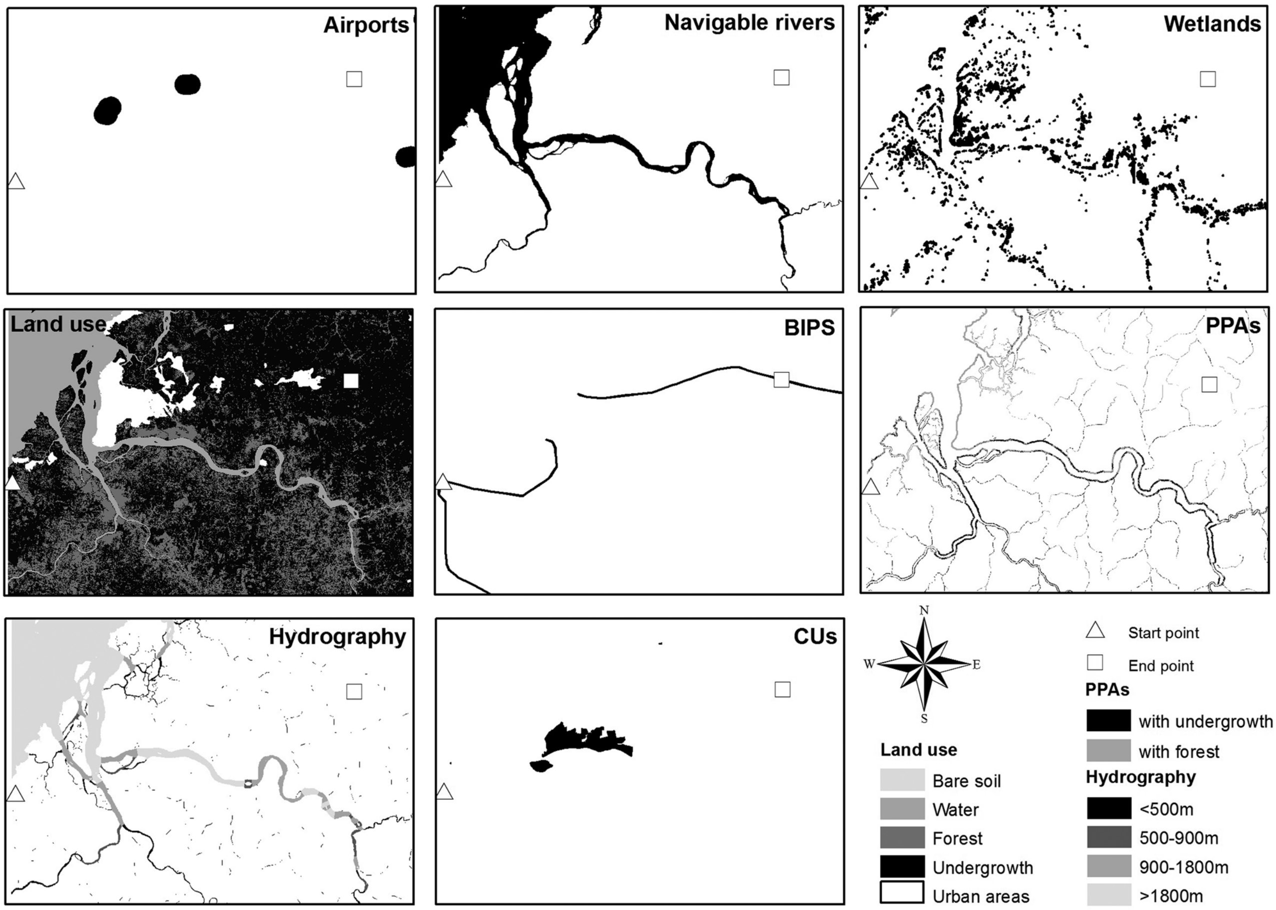


Fig. 6 *Criteria used for case study*

Table 3 Spatial criteria considered in the case study

Criteria	Description
airports	limits of the airports were determined by using high-resolution images from Bing. A distance buffer of 3000 m was considered, according to Brazilian standard [26]
wetlands	wetlands were determined based on satellite images photo-interpretation [27]. A digital elevation model [28] was used to identify the elevation of flooded areas and the layout of their features was carried out by using contour lines
PPAs	these areas were determined based on guidelines established by law N°. 12,651 of 2012 [29]. According to this law PPAs can be defined as protected areas, covered or not by native vegetation with the environmental function of preserving water resources, landscape, geological stability and biodiversity
hydrography	the hydrography was obtained by supervised classification (maximum likelihood algorithm) of satellite images [27]. After this procedure, the water class was isolated, allowing the sectioning of hydrography and determination of the average width of each stretch
navigable rivers	there are four navigable rivers in the study area: Tocantins, Capim, Guama and Moju rivers [30]. The features for this criterion were obtained based on the hydrography criterion
BIPS	the features of this criterion were obtained based on vector data, provided by the Brazilian Ministry of Transport [30]
CUs	the CUs are territorial spaces and their natural resources with relevant characteristics, which were legally instituted with conservation purposes [31]. Despite the restrictive character of intervention within these areas, there are exceptions for the installation of water supply networks, sewage, energy and urban infrastructure in general [31]. The boundaries of CUs presented in the study area were determined based on information available in the website of the Ministry of Environment [32]
land use	this component is primarily related to some aspects: the 'compensation' costs (TL right-of-way); cleaning of ground under TL, environmental compensation in case of elimination of forest fragments in the cleaning strip and use of differentiated towers in areas of forest fragments with ecological importance (higher towers). In this sense, it was considered five land use classes: forest, bare soil, undergrowth, urban areas and water. The features were obtained by supervised classification of satellite images [27]

To obtain the optimised route, the methodology considers the use of two QGIS tools: (i) r.cost.full and (ii) r.drain. The first, using as input a cost surface and the end point of the route, generates as output an accumulated cost surface. This surface is used together with the starting point of the route as input data for the second tool r.drain, which generates the least-cost path.

4 Results and discussions

4.1 Weighting of the criteria

The weights of criteria (Table 4) were normalised by the maximum value (Table 5), which allowed an evaluation of the data distribution for both cost surfaces. The AHP weights had a smaller dispersion, which was confirmed by Pearson's coefficient of variation (3.08 for monetary values and 1.39 for AHP weights). This difference proves that monetary values best represent the criteria, whereas the AHP method tends to generate values closer to the average, which hinders the representation of criteria with significant importance. This can be verified, for example, by 'urban areas' (class of 'land use' criterion). Due to the high costs of compensation (TL right-of-way) in urban areas, this class assumes high values, whereas this class has a relatively lower value in AHP weights (Table 5).

The first analysis of weights is carried out to assess the behaviour of the AHP method to weight the criteria. However, the assessment of the real importance of each criterion for determining the best route cannot be carried out only by analysing the weights assigned to each criterion, because the location and spatial extent of the geographical features of each criterion are of significant importance in defining the route. The wide spatial distribution criteria, i.e. those that occupy large portions of the study area with features distributed homogeneously throughout the place, such as the structures and land use criteria, have great influence on the linearity of the route. If the criterion is concentrated in a specific location (small features) or if it is linear, such as 'airports', 'urban areas' or 'hydrography', it has locational influence and its weight should determine whether the features will be evaded or crossed. These details are assessed and discussed in the next section.

4.2 Determination of optimised routes

The obtained cost surfaces (Figs. 7*a* and *b*) show differences between the AHP weights and the monetary values. The urban areas in the northern part of the study area are highlighted. On the surface of monetary values (Fig. 7*b*) urban spots appear in whiter, whereas in the surface of AHP weights (Fig. 7*a*) urban areas are not obvious, blending the shades with the features of other classes. The accumulated cost surface (Figs. 7*c* and *d*) also demonstrates these facts, where urban areas are more evident on the surface of monetary values (Fig. 7*d*), whereas the

Table 4 Weights by AHP method and monetary values

Criteria	Classes	AHP weights			Monetary values, US$/km
		Weight of variable (WV)	Weight of class (WC)	Final weight (WV × WC)	
airports	—	13.8	100	1,380.00	5,283,391.41
wetlands	—	13	100	1,300.00	422,469.47
PPAs	PPAs with undergrowth	4.4	25	110.00	46,758.60
	PPAs with forest		100	440.00	31,172.40
hydrography	<500 m	39.4	—	568.60	543,808.21
	500–900 m		17.65	695.29	1,140,046.42
	900–1800 m		100.00	3,940.00	2,087,454.73
	More than 1800 m[a]		—	10^9	10^9
navigable rivers	—	7.2	100	720.00	613,314.01
BIPS[b]	—	–2.8	100	–280.00	–20,903.04
CUs	—	12.1	100	1,210.00	31,172.40
land use	undergrowth	3.2	8.32	26.62	41,806.08
	forest		40.19	128.60	512,635.81
	water		0.00	0.00	0.00
	urban areas		100.00	320.00	11,799,703.76
	bare soil		8.32	26.62	9,886.08
structures	—	4	100	400	754,770.20

[a] This class is considered as an impediment. Thus, it assumes a significant greater value in relation to the other classes

[b] This criterion is considered as an attractor (generates cost savings), unlike other criteria, explaining negative value

Table 5 Criteria weights normalised by the maximum value

Criterion	Classes	(Value/maximum) × 10^4	
		AHP weights	Monetary values
airports	—	3,503	1,119
wetlands	—	3,299	90
PPAs	PPAs with undergrowth	279	10
	PPAs with forest	1,117	7
hydrography	<500 m	1,443	115
	500–900 m	1,765	242
	900–1800 m	10,000	442
navigable rivers	—	1,827	130
BIPS	—	−711	−4
CUs	—	3,071	16
land use	undergrowth	68	9
	forest	326	109
	urban areas	812	10,000
	bare soil	68	2
structures	—	1,015	160
Pearson's coefficient of variation		1.39	3.08

hydrography is less evident for this surface (Fig. 7*d*). Besides these aspects, the methodology used by accumulation function (Dijkstra's algorithm) is clearly highlighted in spatial representation of accumulated costs surface, where lower values are found near the end point of the route, and from that point the values increase radially (Figs. 7*c* and *d*).

The generated routes and the TL Vila do Conde-Castanhal are compared in relation to total cost (by overlapping the surface of monetary values) and the overall length (Table 6). The route obtained by the monetary values surface appeared more linear and with lower length value. This result can be explained mainly by two criteria, as well as by the weight values assigned to these two criteria and spatial distribution of their features: (i) 'structures', which had the greatest influence on linearity, and (ii) 'hydrography', which influences the river crossing point and, therefore, the overall length of the route.

Table 6 Total cost (overlapping the surface of monetary values) and length of the generated routes compared with the TL Vila do Conde-Castanhal

Route	Total cost, US$	Length, km	Cost reduction, %
monetary values	101,600,047.69	118	12
AHP weights	109,177,316.52	130	5
TL Vila do Conde-Castanhal	115,216,235.39	138	—

(i) The 'structures' criterion has a significant influence on the linearity of the route due to its wide spatial distribution, since it is a single value surface with full coverage of the study area. In principle, an analysis of the normalised weight values (Table 5) indicates that the structures criterion has greater significance for the set of AHP weights. This contradicts the obtained results, where the route generated through AHP weights is more curvy than the one generated based on monetary values. However, the analysis of the importance of the criteria in the route cannot be

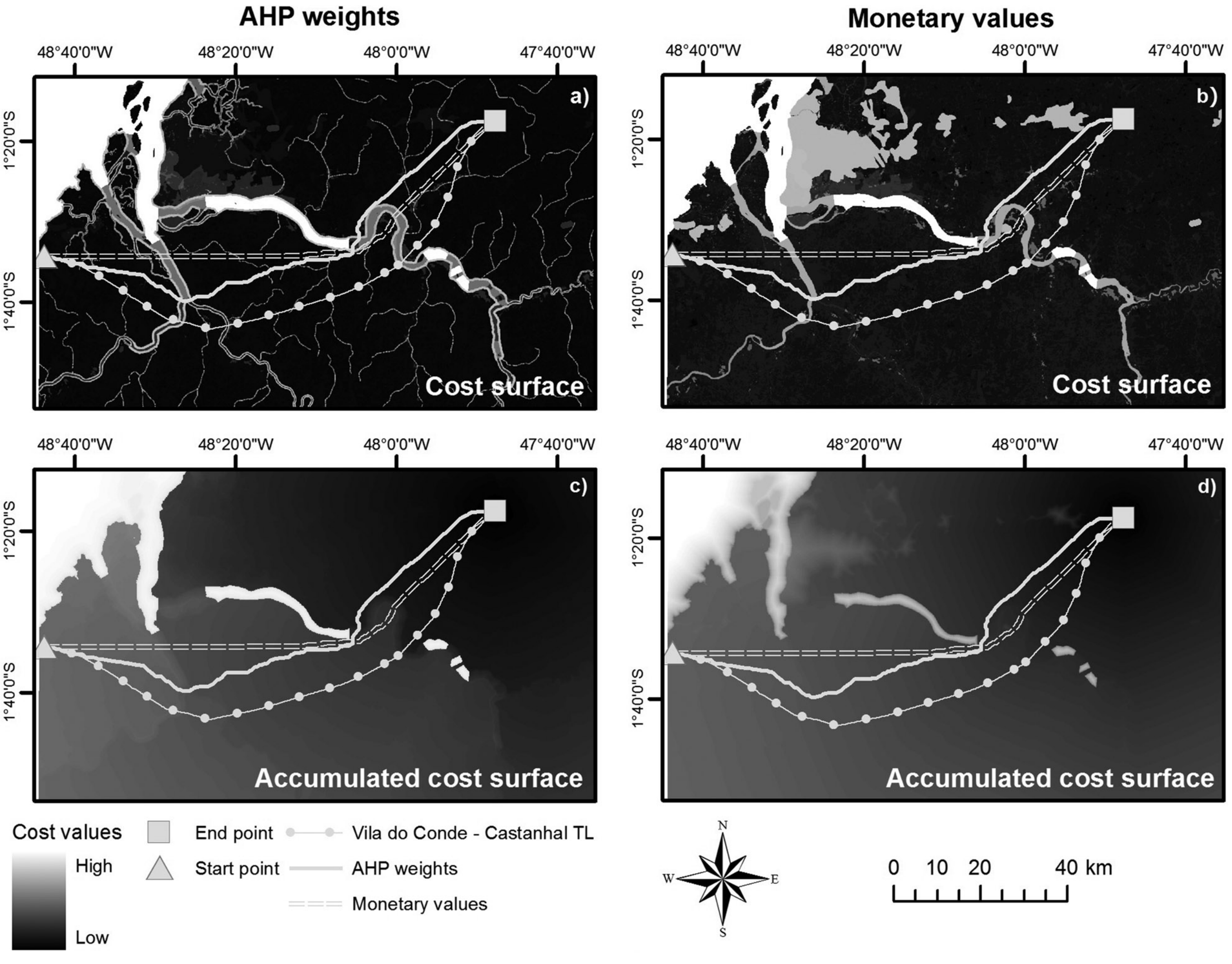


Fig. 7 *Results of application of least-cost path tools of QGIS*

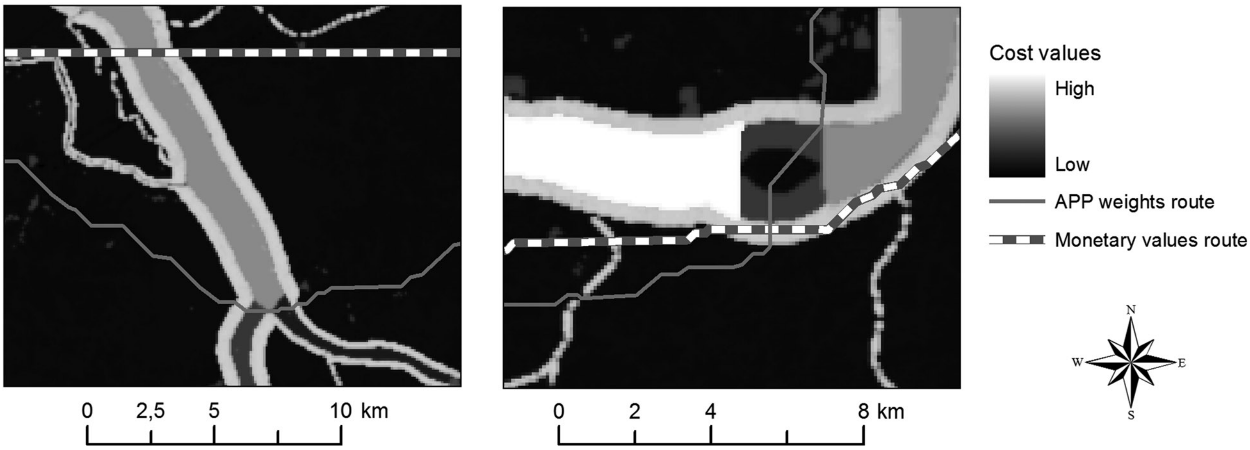


Fig. 8 *Comparison of crossing points of hydrography by routes of monetary values and AHP weights*

made only by the assessment of the associated weight, but the spatial distribution of criteria must also be considered. Therefore, the calculation of standardised weights by the maximum value is carried out regardless of 'urban areas' and 'airport', because these classes received the highest weights and their geographic features are more concentrated and distant from the preferred direction of the route. The standardised weights for the 'structures' criterion resulted in 3116 and 1015 for the sets of monetary values and AHP weights, respectively. It shows the importance of the criterion 'structures' in the linearity of the route. Therefore, although the used algorithm (Dijkstra's algorithm) does not incorporate changes of direction in the route as in [1], the 'structures' criterion indirectly models the influence of the TL deflection angle, knowing that sharp angles require more reinforced structures [2] and the higher the value of the 'structures' criterion the more linear the route becomes. At this point, it is interesting to note the results obtained by Yildirim and Nisanci [11] in a TL routing in Turkey. The authors did not use a 'structures' criterion to incorporate the base costs, and the modelled route presented a greater length. However, it crossed fewer areas of social and environmental importance.

(ii) Regarding the 'hydrography' criterion, the route generated from the AHP weights crossed hydrography in narrower passages, but through a longer route (Fig. 8). The analysis of Table 5 indicates that the 'hydrography' class from 900 to 1800 m wide have a higher significance for the AHP surface. In addition, the standardised weight values for the 'PPAs' criterion are greater for the surface of AHP weights, which also influence the point of hydrography crossing. These facts, along with the minor importance of structures criterion on the AHP surface, led the route of this surface to cross the hydrography in portions of smaller width, but through a longer way.

5 Conclusion

This paper presents a TL route optimisation methodology based on GIS and AHP, where the applicability is verified by using a pilot area in the state of Pará, Brazil – 230 kV TL Vila do Conde-Castanhal. The effectiveness of the AHP method is assessed by comparing its results with the results obtained by the use of monetary values to weight the criteria.

The AHP method demonstrated lower capability to represent the criteria when compared with the monetary values. The route generated by using AHP weights presented total cost and total length greater than the route generated by using monetary values. However, these results do not exclude the possibility of using AHP for route planning, once the practicality of AHP when compared with assigning monetary values to the criteria, AHP generated a route with length and total cost smaller than the existing TL.

In general, the GIS least-cost path tools used for route optimisation generated satisfactory results with routes of shorter length and lower cost in relation to the existing TL. However, despite the application of structures criterion as a form of representation of the basic structural implementation costs, which influence the linearity of the route, the influence of the deflection angle is not considered in the algorithm. Thus, it is recommended the assessment of the algorithm structure and its modification considering the deflection angle in future studies.

6 Acknowledgments

This work was developed in the context of the project 'PD-2651-0008/2013: 'Development of software for TL route optimization by use of environmental risks analysis and enhanced geotechnical-assessment', proposed by EATE; in cooperation with ERTE, ETEP, Lumitrans, STC; managed by TBE; and carried out by iX Estudos e Projetos, with resources from ANEEL R&D program 2012/2014.

7 References

1 Monteiro, C., Ramírez-Rosado, I., Miranda, V., *et al.*: 'GIS spatial analysis applied to electric line routing optimization', *IEEE Trans. Power Deliv.*, 2005, **20**, (2), pp. 934–942

2 Kiessling, F., Nefzger, P., Nolasco, J.F., *et al.*: 'Overhead power lines: planning, design, construction' (Springer-Verlag Berlin Heidelberg Press, 2003)

3 Schmidt, A.J.: 'Implementing a GIS methodology for siting high voltage electric transmission lines' (Papers in Resource Analysis, Saint Mary's University of Minnesota University Central Services Press, Winona, MN, 2009), vol. 11, p. 17

4 Husain, F., Sulaiman, N.A., Hashim, K.A., *et al.*: 'Multi-criteria selection for TNB transmission line route using AHP and GIS'. 2012 Int. Conf. on System Engineering and Technology, Bandung, Indonesia, 2012

5 Eroglu, H., Aydin, M.: 'Optimization of electrical power transmission lines' routing using AHP, fuzzy AHP, and GIS', *Turk. J. Electr. Eng. Comput. Sci.*, 2015, **23**, pp. 1418–1430, doi: 10.3906

6 Recio, M.R., Seddon, P.J., Moore, A.B.: 'Niche and movement models identify corridors of introduced feral cats infringing ecologically sensitive areas in New Zealand', *Biol. Conserv.*, 2015, **192**, pp. 48–56

7 Sitzia, T., Rizzi, A., Semenzato, P.: 'Designing recreational trails in a forest dune habitat using least-cost path analysis at the resolution of visitor sight distance', *Urban Forestry Urban Greening*, 2014, **13**, pp. 597–900

8 Carotenuto, F., Tsikaridze, N., Rook, L., *et al.*: 'Venturing on safely: the biogeography of *Homo erectus* dispersal out of Africa', *J. Hum. Evol.*, 2016, **95**, pp. 1–12

9 Effat, H.A., Hassan, O.A.: 'Designing and evaluation of three alternatives highway routes using the analytical hierarchy process and the least-cost path analysis, application in Sinai Peninsula, Egypt', *Egypt. J. Remote Sens. Space Sci.*, 2013, **16**, pp. 141–151

10 Dedemen, Y.: 'A multi-criteria decision analysis approach to GIS-based route selection for overhead power transmission lines'. PhD thesis, Graduate School of Natural and Applied Sciences of Middle East Technical University, 2013

11 Yildirim, V., Nisanci, R.: 'Developing a geospatial model for power transmission line routing in turkey'. Spatial Information Modeling II. FIG Congress 2010, Facing Challenges – Building the Capacity, Sydney, Australia, April 2010

12 Bagli, S., Geneletti, D., Orsig, F.: 'Routing of power lines through least-cost path analysis and multi-criteria evaluation to minimize environmental impacts', *Environ. Impact Assess. Rev.*, 2011, **31**, pp. 234–239

13 Li, Y., Yang, Q., Sima, W., *et al.*: 'Optimization of transmission-line route based on lightning incidence reported by the lightning location system', *IEEE Trans. Power Deliv.*, 2013, **28**, (13), pp. 1460–1468

14 EPE. Energy Research Office: 'Studies for the expansion of transmission, consolidation of the analysis and technical reviews: expansion transmission programme (PET)/long term expansion plan (PELP) 2015 cycle – second half'. Rio de Janeiro – RJ, 2015

15 U.S. Energy Information Administration: 'Today in energy: electricity transmission investments vary by region', 3 September 2014

16 Collischonn, W., Pilar, J.V.: 'A direction dependent least-cost-path algorithm for roads and canals', *Int. J. Geogr. Inf. Sci.*, 2000, **14**, (4), pp. 397–406

17 Etherington, T.R.: 'Least-cost modeling on irregular landscape graphs', *Landsc. Ecol.*, 2012, **27**, pp. 957–968

18 Tomlin, C.D.: 'Cartographic modeling', in: 'Geographic information systems' (Wiley Press, 1991, 1st edn.), pp. 361–374. Available at http://www.wiley.com/legacy/wileychi/gis/Volume1/BB1v1_ch23.pdf, accessed 18 November 2015

19 Saaty, T.L.: 'How to make a decision: the analytic hierarchy process', *Eur. J. Oper. Res.*, 1990, **48**, pp. 9–29

20 Saaty, T.L., Vargas, L.G.: 'Comparison of eigenvalue, logarithmic least squares and least squares methods in estimating ratios', *Math. Model.*, 1984, **5**, pp. 309–324

21 Goepel, K.D.: 'BPMSG AHP excel template with multiple inputs, version 12.08.2013, AHP analytic hierarchy process (EVM multiple inputs)', 2013. Available at http://bpmsg.com/new-ahp-excel-template-with-multiple-inputs, accessed: 19 October 2013

22 Wolsey, L.A., Nemhauser, G.L.: 'Integer and combinatorial optimization' (Wiley, 1999), p. 784

23 Dijkstra, E.W.: 'A note on two problems in connection with graphs', *Numer. Math.*, 1959, **l**, pp. 269–271

24 Cormen, T.H., Leiserson, C.E., Rivest, R.L., *et al.*: 'Introduction to algorithms' (The MIT Press, Massachusetts Institute of Technology, 2009, 3rd edn.)

25 ERTE. Regional Power Transmission Company.: 'Technical executive projects of TL Vila do Conde – Castanhal – Santa Maria – 230kV', 2003. Data provided by TBE (Brazilian power transmission companies)

26 ICA 63-19: 'Technical assessment criteria of airport areas' (Ministry of Defence, Aeronautical Command, Department of Airspace Control, Brazil, 2015)

27 LANDSAT 5 TM: 'Scene 223-61, date: 2008.07.13', obtained from INPE (National Institute for Space Research), image data base: http://www.dgi.inpe.br/CDSR/, accessed 2015

28 Miranda, E.E., Guimarães, M., Hott, M.C., *et al.*: 'Brazilian topography', Campinas: EMBRAPA satellite monitoring, 2005, Available at http://www.relevobr.cnpm.embrapa.br, accessed 2015

29 Brazil: 'Law 12.651 – May 25, 2012'. Available at http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm, accessed 2015

30 PNLT – National Plan for Logistics and Transport: 'georeferenced data base', 2010

31 Brazil: 'Law 9.985 – July 18, 2000', Available at http://www.planalto.gov.br/ccivil_03/leis/l9985.htm, accessed 2015

32 MMA – Ministry of Environment: 'Brazilian Conservation Units' (Vector data on shp format, 2014, Available at http://mapas.mma.gov.br/i3geo/datadownload.htm, accessed 2015

33 Aneel. Brazilian Electricity Regulatory Agency: 'Reference prices 06/2013', transmission lines budget, 2013