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Optimizing routing and tower spotting of electricity transmission lines: An integration of geographical data and engineering aspects into decision-making

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A R T I C L E I N F O

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A B S T R A C T

In many parts of the world, electric sectors are already experiencing considerable rising in generation from renewable energy sources. Large amounts of new generation are expected in the near-term future, which will require additional transmission investments to properly integrate these resources into the existing electric power system. The transmission expansion planning has an important role in this environment in order to guarantee the security of the supply with the required levels of quality and price. Therefore, the implementation of new transmission lines (TL) must be fast and accurate in order to avoid delays to connect new power sources and potential supply and reliability problems. In this sense, Geographical Information Systems (GIS) can be a powerful tool that provides decision support techniques, which enables a transparent, sustainable, faster planning process for TLs in power systems. This paper presents a novel approach for the design of overhead TLs, considering geographical, engineering and cost aspects into the decision-making process. For this, routing and tower spotting optimization approaches are integrated into the proposed methodology, which is divided into three main steps: (i) Route Guideline Definition based on a raster-based least-cost path approach; (ii) Vertex Siting based on graph theory and the Dijkstra shortest path algorithm, applied in order to find the optimal vertex set along the route guideline; (iii) Tower Spotting based on Dynamic Programming, which is applied in order to find the optimal distribution of towers along the topographical profile of the route obtained in the previous step. The proposed methodology is focused on preliminary planning and decision-making for TL auctions, where the objective is to find design alternatives with the least cost. We show a case study using the proposed methodology for a real project of a 525 kV TL that interconnects Machadinho and Campos Novos (located in the Santa Catarina state in Brazil). The outcomes show that the proposed approach is capable of representing the technical and geographical constraints of a TL design, providing results with lower costs when compared to the original TL design.

1. Introduction

Concerns regarding climate change have increased in recent years, implying efforts of many countries towards the reduction of greenhouse gas (GHG) emissions [1]. As a result, the electric sector is already experiencing a considerable increase in generation from renewable energy sources (RES) [2]. By 2022, global renewable electricity generation is expected to grow by over one-third, reaching 8 thousand TWh [3]. For Brazil, it is expected that 75% of electricity generation expansion until 2026 should be from renewable sources. From that, 50% are of non-hydro sources, mainly wind and solar [4]. The large amounts of new generation expected in the medium-term future will require additional

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transmission investments for its integration into the system [5].

Unlike conventional fossil fuel-based power sources, the site selection for renewable power sources has few or no degrees of freedom. Also, viable renewable energy sites are usually located far away from energy consumption centers and existing infrastructure. Besides such location constraints, renewable energy sources are usually granular and dispersed. For example, to get the same power of a large hydroelectric by using only wind power, the development of several dispersed wind farms will be necessary, all of which in turn will require proper transmission infrastructure. This way, these characteristics of renewable power sources bring implementation challenges for transmission utilities from the planning, construction, and environmental point of view [6]. The growing concerns about social and environmental aspects add even more complexities to transmission planning. For example, the author in Ref. [7]. states that in the last decades in Switzerland numerous laws and ordinances prescribing measures to protect the environment and landscape have been issued, which makes the expansion of the Swiss electricity grid proceeding slowly.

Brazil also faces problems related to delays in the construction of new transmission lines (TLs). According to Ref. [8], about 12,500 km of TLs that should be operating have some problem or delay, which shows fragilities of the planning, design, and construction steps. One of the possible sources of these fragilities could be the spatial planning of new TLs into Brazilian transmission planning and bidding. The electrical planning process, organized and performed by the Brazilian Federal Government, defines the new TLs to be implemented, which is made primarily considering electric aspects. These TLs are contracted by procurement auctions, organized by Brazilian Electricity Regulatory Agency - ANEEL, where the winning bid is the proposal requiring the least revenue during the 30 years concession period [9]. The geographical planning of a new TL can be considered preliminary before the auction since the TL route are defined as a guideline from regional studies. The final route and the vertex location will be defined only after the auction, during the base project elaboration, by the winner company. After acceptance of the base project by ANEEL, the executive design begins to be drawn up, where the final structural component design and tower spotting are performed.

The issues and constraints mentioned above show an evident need for new tools and methodologies to improve the planning procedure of new TLs. According to Ref. [6], the clear need to scale up transmission investments in order to support the growth of renewable power sources shows that planning is an important factor in ensuring that these investments are developed in a timely and cost-effective manner. In this sense, Geographical Information Systems (GIS) can be a powerful tool, providing decision support techniques and hence allowing a transparent, sustainable, faster planning process of electric supply grids [7]. According to Ref [10]. GIS techniques can be applied as a decision support tool involving the integration of geographical data in the problem solving, which have an important role to play in analysing decision problems.

Given the exposed environment, this paper presents a novel approach for the previous design of overhead TLs, considering geographical, engineering and cost aspects into the decision-making process. For this, routing and tower spotting optimization are integrated into the methodology in order to find the least cost alternative design of a TL. The use of the proposed methodology creates a better understanding of the TL design in the preliminary steps of the planning process, which can reduce the investment risks and construction lead time. The methodology is tested considering a real TL project representing the existing 525 kV Machadinho - Campos Novos TL (located in the Santa Catarina state, Brazil). The remainder of the paper is structured as follows. Section 2 gives an overview of optimization techniques applied for routing TL and tower spotting and shows the contributions of this paper in relation to previous works. In Section 3 the proposed methodology is presented. The description of the case study is presented in Section 4. In Section 5 the results are presented, discussed and compared with the original TL design. Finally, Section 6 presents remarks and main conclusions.

2. Optimization applied to route selection and tower spotting

Basically, the design of a TL can be divided into three main steps: (i) electrical design, (ii) structural component design and (iii) final line design. In the first one, the line configuration is determined, such as the number and size of sub-conductors and ground wires and tower geometry. The objective of this step is to select the electric factors configuration that gives the maximum power transfer capacity and lowest total cost of the line. In the second step the choice of conductor and conductor bundle, ground wires, insulation, hardware, structures, foundations and earthing is rigorously considered. A relevant characteristic of this step is the use of a database of components already designed, such as conductors, supporting structures and foundations. Finally, in the last step, the final route will be selected and the tower spotting will be performed, based on route relief obtained from a Digital Terrain Model – MDT [11,12].

The transmission line routing is considered as an optimization task that aims to minimize the implementation and operation costs, as well as the environmental and landscape impacts. Considering only the technical aspects, a straight line is the best alternative, since angle points are associated with higher mechanical efforts, and consequently with more expensive structures [12]. However, the route of a TL is determined based on various constraining criteria, such as right-of-way and landowner issues, soil conditions, road, and other clearances, cost and regulatory issues as construction access [13]. In relation to environmental and landscape aspects, the author in Ref. [14] listed 6 main objectives for the route selection: (1) to minimize damage to natural systems; (2) to minimize conflict with existing land use; (3) to minimize conflict with proposed land use; (4) to maximize potential for right-of-way sharing; (5) to minimize impact on culturally significant features; (6) to minimize visual impact. On the other hand, the total cost of the TL project is a decisive aspect for the route selection of a transmission line, where the additional costs due to environmental and landscape constraints can be considered in order to find the suitable route alternative [15,16].

Overall, the selection of the mains aspects and criteria for a successful project of a TL depends on the geographical characteristics of the study area. In Brazil, for example, for the Amazon region, environmental constraints and soil conditions are important aspects for the route selection. The occurrence of low resistance soil associated with fluvial areas is associated with higher costs for foundations. Preservation areas can be prohibitive areas or can demand the use of special structures in order to reduce the deforestation areas [16,17]. Air quality and lightning incidence can be also relevant for certain areas since these aspects can lead to problems with insulation and electrical fails [18–20].

This way, the route selection of a TL is essentially a problem in the field of geographical studies and spatial analysis methods are fundamental tools in the planning process [14]. Routing techniques have evolved through the years, and today Geographic Information Systems (GIS) approaches allow designers to easily identify suitable land corridors [21]. Among the available GIS-based techniques, the computation of least-cost path (LCP) over a cost-surface, an approach commonly called raster-based LCP analysis, is well-known and widely employed to support route design of TLs [7,15,16,21,22], and planning and design of other different types of linear infrastructures [23–26].

The cost-surface is represented as a raster map, where each cell has a weight that represents a resistance or friction to cross it and can express cost, time, distance, environmental impact, or other aspects [23]. The cost surface can integrate all the criteria that affect the routing process, selected according to the purpose of the study. In a routing transmission line study, focused on minimizing environmental impacts, the author in Ref. [21], selected criteria regarding human health (such as population density and distance from buildings), landscape (such as distance and visibility from cultural and recreational sites and visibility from residential buildings) and nature (such as naturalness land cover and ridges). The authors in Refs. [15,16] used a cost-surface to model the implementation costs of a TL in order to perform least-cost path analysis. The authors divided the implementations costs into two main groups: (i) non-geographical costs, related to equipment of the TL; and (ii) geography-dependent costs, such as accessibility costs, additional costs due to the specific characteristics and constraints of the study area (landowner and vegetation cleaning costs related to the land use, additional costs according to the soil type, costs to cross obstacles, such as roads, rivers, telecommunication, and other TLs).

Despite their popularity and efficiency, raster-based methodologies for TL routing present some important limitations. The rectangular aspect of the raster surface causes distortions and an excessive number of vertices in the modelled route, mainly due to the limited possibilities of directions, defined by the neighbourhood between pixels [7,27]. In addition, some technical aspects cannot be considered in the optimization, such as the influence of deflection angle and topography in the implementation costs, aspects that will be considered only in further steps of the TL design. The author in Ref. [7]. presents a methodology integrating tower spotting and route definition into a single algorithm, where the influence of topography and deflection angle in the TL routing is considered. As the main constraint of the methodology, the author highlighted the computational demand needed to run the algorithm. For this reason, the author considered a single type and height of towers.

Since the final alignment of the TL is defined, the potential structure locations are identified along the route using tower spotting process. Tower spotting process is a design process which determines the location, height, and type of consecutive towers of the TL, which is performed based on terrain, land use, and geographical restrictions. The main technical factors to be considered for the tower spotting are clearances, structure capacity and conductor uplift [13]. A small number of studies have focused on optimization techniques applied to tower spotting. The author in Ref. [28] presented an algorithm based on Dynamic Programming (DP), where two different types of towers (anchor and suspension) and different heights are considered. However, the results obtained had no significant impact, due to the computational limitations of the machine used to run the tests. The author in Ref. [29] described a DP algorithm which chooses the height and sites of the suspension towers of a TL in order to minimize the overall cost. The constraints considered in the optimization were a maximum single span, uplift, and statutory clearance. The authors tested the algorithm on a twenty-mile stretch of a 400 kV TL and reported a cost saving of 7%.

According to the author in Ref. [30], previous studies applying DP to tower spotting contain some inaccuracies and the absolute minimum cannot be guaranteed. The decision was taken at the nth position results in only one variant of tower distribution moving back from this position, which cannot ensure the absolute optimal solution. In order to solve this issue, the author in Ref. [30] developed a method based on DP for the choice of types, heights, and sites of towers along the TL route that allows finding the absolute optimal solution. For this, the algorithm proposed by the author enables the determination of a set of consecutive cheapest solutions to the problem, in other words, the optimal solution and the required number of suboptimal solutions. In addition, the algorithm described in Ref. [30] considers the application of anchor towers for straight sections of the route, different to previous studies that allow only suspension towers for straight sections. According to the author in Ref. [30], this contribution reflects the optimal solution, since anchor towers can be applied to crosses major objects, or even to better allow major spans to take advantage of relief shape.

This work proposes a novel approach, where the result of a least-cost path raster based methodology, interpreted as a route guideline, is used as the main input for a vertex siting algorithm that considers technical and geographical constraints. As a result, an optimal set of vertices is defined, which represents the final route of the TL, without distortions and with a reasonable number of vertices. The final route is the main input of a third step, the tower spotting, which aims to find the optimal distribution of towers along the topographic profile. The structure of the methodology proposed in this paper is significantly less complex compared to the approach proposed by Ref. [7] since the tower spotting is addressed separately from the route guideline definition and vertex siting. It allows the technical and geographical constraints to be addressed in detail in each step, increasing the precision and reliability of the results considering the methodology as a whole.

3. Methodology

The proposed methodology is divided into three main stages (Fig. 1): (i) Route Guideline Definition based on a raster-based least-cost path approach; (ii) Vertex Siting based on graph theory and Dijkstra algorithm, in order to find the optimal set of vertex distributed along the route guideline, which defines the final route of the TL; (iii) Tower Spotting based on Dynamic Programming, in order to find the optimal distribution of towers along the route obtained in the previous step. Since the analysis is focused on decision-making for TL auctions and the objective of the methodology is to find the design alternative with the least cost, the optimization criteria adopted for each step is the TL implementation costs. The Operations and Maintenance (O&M) costs are not considered here since the methodology proposed is focused on preliminary planning. However, the methodology is flexible to include new constraints and cost elements, such as O&M costs.

3.1. Route guideline definition

The optimal route guideline is calculated using a raster-based least-cost path approach (Fig. 2), where the mathematical model and the optimization algorithm is described in Ref. [16]. The first step is to construct a cost surface that models the geographical distribution of the TL implementation costs over the study area, expressed in R$/km. This surface should include every criterion related to the implementation costs, selected according to TL technical aspects and geographical characteristics of the study area. Considering the Transmission Budget Methodology [31], which is used to calculate the baseline prices of the Brazilian auctions of TLs and substations, the criteria that integrate the cost surface are divided into four groups: (i) Base Cost - BC, (ii) Structural Additional Costs - SAC, (iii) Right-of-Way Costs - RWC and (iv) Impediments - IMP.

The BC represents the equipment costs of a TL (conductors, towers, foundations, topography and geotechnical surveys, grounding, among others), considering a TL crossing an area without any restriction such as conservation areas and erosion susceptible areas. Unlike the other cost groups that are geographically dependent and can be represented by multiple geographical criteria, the BC has no geographical dependence and can be represented by a raster map with a single value for every cell. However, this surface has a significant influence on the route shape. As suggested by the authors in Ref. [16], this surface influences 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. The BC cost value is estimated considering an average span, average tower height and a certain proportion of anchor and suspension towers. The exact values of these parameters can be calculated only after the tower spotting step when the location of vertices and towers is known. Therefore, the values of these parameters in this step are defined as a previous estimate according to relief characteristics and geographical constraints of the study area.

The SAC group represents the additional costs in relation to the BC, related to restrictions geographically distributed over the study area, such as: low resistance soils, which require the application of special foundations; erosion susceptible areas, which require special

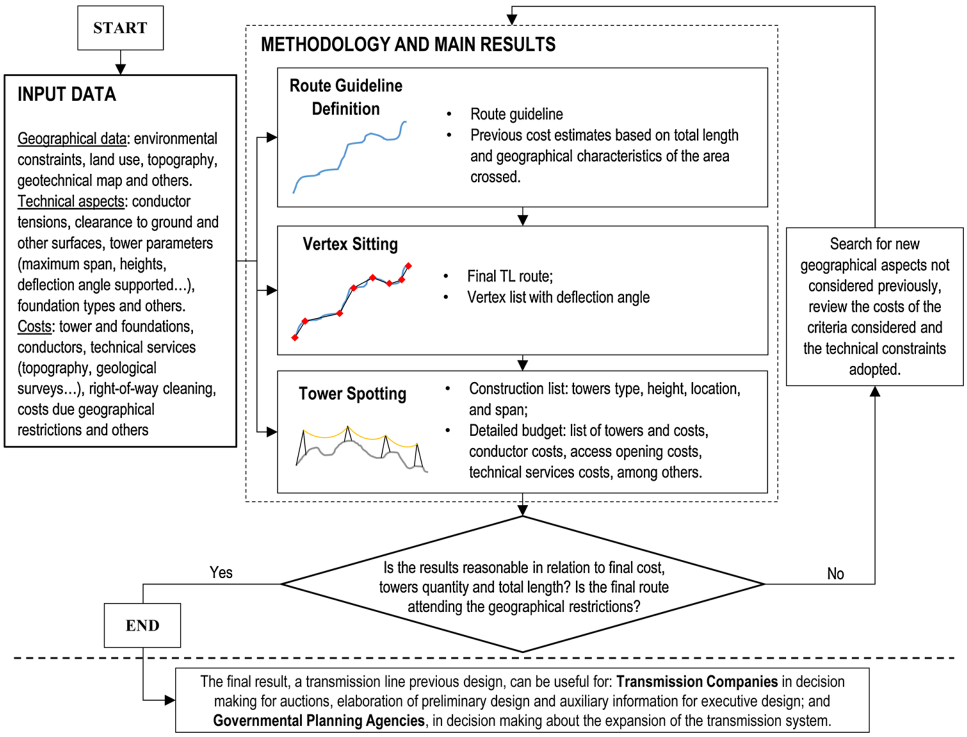

Fig. 1. Overview of the proposed methodology.

construction methods to avoid erosion; preservations areas, which can require the use of taller towers to avoid or reduce deforestation; rivers and reservoirs, which can require special towers and even special conductors to cross wider sections, and, if it is navigable, taller towers are required in order to respect the higher clearance.

The RWC group is composed mainly of costs associated with the right-of-way, such as landowner compensation, deforestation and cleaning costs. These costs are determined according to the land-use along the TL route, for example, agricultural areas may have higher compensation costs and forested areas should have higher costs for cleaning than pasture areas. The costs to construct new access to equipment mobilization and material delivery are also included in the RWC group, which is calculated considering the conditions of the access infrastructure existent in the study area.

The IMP criterion has no costs associated and represents areas that should be avoided, such as urban areas, mountains and lakes or rivers from a determined extension. The impediments are represented by null values (no-data) in a raster file, interpreted by least cost path algorithms as "holes" in the surface and consequently as regions impossible to cross.

The costs associated with each criterion should be calculated or estimated and for this paper, the price database from the Transmission Budget Methodology [31] was used for all costs estimates. Using the costs previously calculated, the criteria are integrated by map algebra using the software QGIS, in order to obtain the cost surface in raster format (*.tiff). This file and the spatial coordinates of the start point of

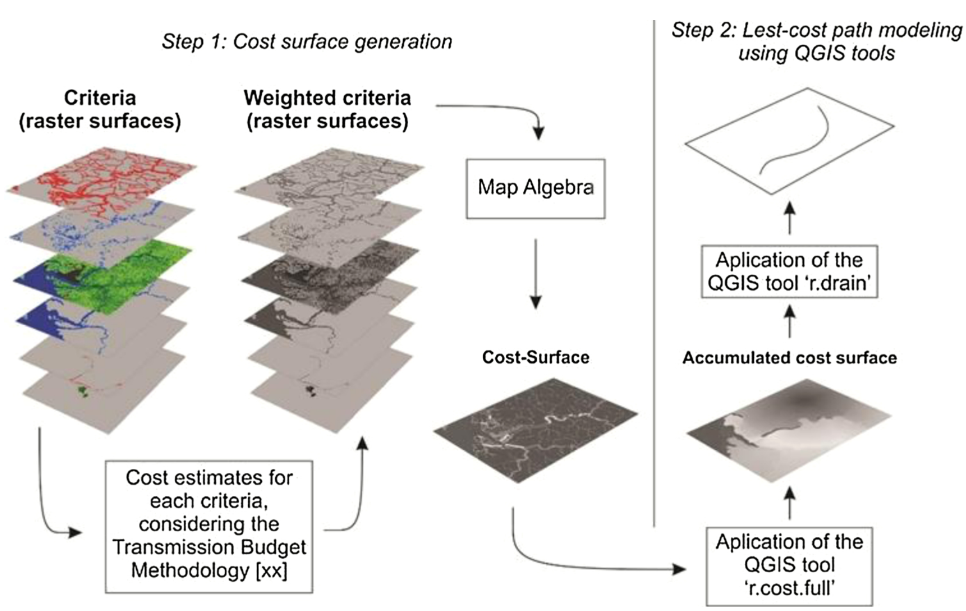

Fig. 2. Flowchart of the methodology applied for the route guideline definition.

the TL are used as input of the r.cost.full QGIS tool, in order to generate an accumulated cost surface, also in raster format. This surface and the end point of the TL are used as input of the r.drain QGIS tool, which generates the least cost-path that represents the optimal TL guideline.

3.2. Vertex siting

As described in previous works, the raster-based approach for least cost-path analysis generates routes with a certain level of distortions [7,27] and a high number of vertices, which do not represent realistically a TL route. In order to solve this issue and rectify the route generated in the previous step, a methodology for vertex siting based on graph theory is proposed. As a result, an optimal set of vertices is defined, considering technical and geographical constraints.

The methodology proposed is divided into two main steps: (i) construction of a graph that represents the connection possibilities between the points along the route; (ii) application of the Dijkstra's algorithm [32] to find the vertex set that results in the least implementation cost.

3.2.1. Graph construction

The route guideline is divided into a set P of n points interpreted as possible places to set as a vertex. Points located inside rivers, reservoirs and valley bottom are excluded from the analysis and considered as impediments to the vertex siting (Fig. 3). Given the graph G (V, E), the set of nodes $V = (v_1, \ldots, v_n)$ consists of the set P. The set of edges $E = (e_1, \ldots, e_n)$ is obtained by computing the connections between each node v_i and all the subsequent nodes $(v_{i+1}, \ldots, v_n)$ and represents linear stretches of the TL. A deviation tolerance from the original route is considered to define E (Fig. 3), wherein the edges that do not respect the deviation tolerance are not considered.

Since the optimization model seeks to minimize the TL implementation cost, the nodes and edges costs shall be calculated. The edges cost are defined as a single average cost per kilometer considering only suspension towers, an average span and an average tower height. On the other hand, the cost of a given node from the set N is the cost of the tower applied, which is chosen according to the deflection angle of this node. The deflection angle, in turn, depends on the pair of subsequent edges that shares this node. As a result, each node has multiple values of deflection angle, depending on the combination of edges. Consequently, the node costs cannot be modelled by the structure of the graph G.

In order to solve this issue, the graph G is transformed into a dual graph D (V^D, E^D) that is the edge-based representation of the graph G [33]. The set $V^D = (v_1^D, \ldots, v_m^D)$, corresponds to the set of edges E of the graph G. Each element of $E^D = (e_1^D, \ldots, e_k^D)$ corresponds to a pair of adjacent edges of the graph G, forming a deflection angle α_{ij}, with $i \neq j$ and $i, j \in V^D$. Given this graph D, each node pair $(i, j) \in E^D$ has a cost value calculated by Eq. (1).

$$c_{ij} = f(\alpha_{ij}) + \frac{l_{ij}}{2}.\, S \tag{1}$$

where:

c_{ij} — is the total cost of the edge $(i, j) \in E^D$

$f(\alpha_{ij})$ — is the cost of the tower selected according to the deflection angle α_{ij};

l_{ij} — is the total length of the linear TL stretches that compose the edge $(i, j) \in E^D$;

S — is an average cost in US$/km considering only suspension towers, an average span and an average tower height.

3.2.2. Calculation of the least cost set of vertex

Given the graph D described above, consider the following mathematical model (2):

$$C_{Total} = \min_{x_{ij}} \sum_{ij \in E_D} c_{ij} x_{ij} \tag{2}$$

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

$$\sum_j x_{tj} - \sum_j x_{jt} = -1 \tag{2b}$$

$$\sum_j x_{ij} - \sum_j x_{ji} = 0 \quad \forall\, i \in \frac{N_D}{\{s,\, t\}} \tag{2c}$$

$$x_{ij} \geq 0 \quad \forall\, ij \in E_D \tag{2d}$$

Decision variables x_{ij} indicate whether an edge (i, j) is part of the shortest path. The goal is to select the set of edges that form the minimal total cost (C_{Total}) to go from source node s to sink node t, corresponding to the subset of E_D that represents the lowest cost route for the TL. Eq. (2a) requires that only one edge is active going from s to

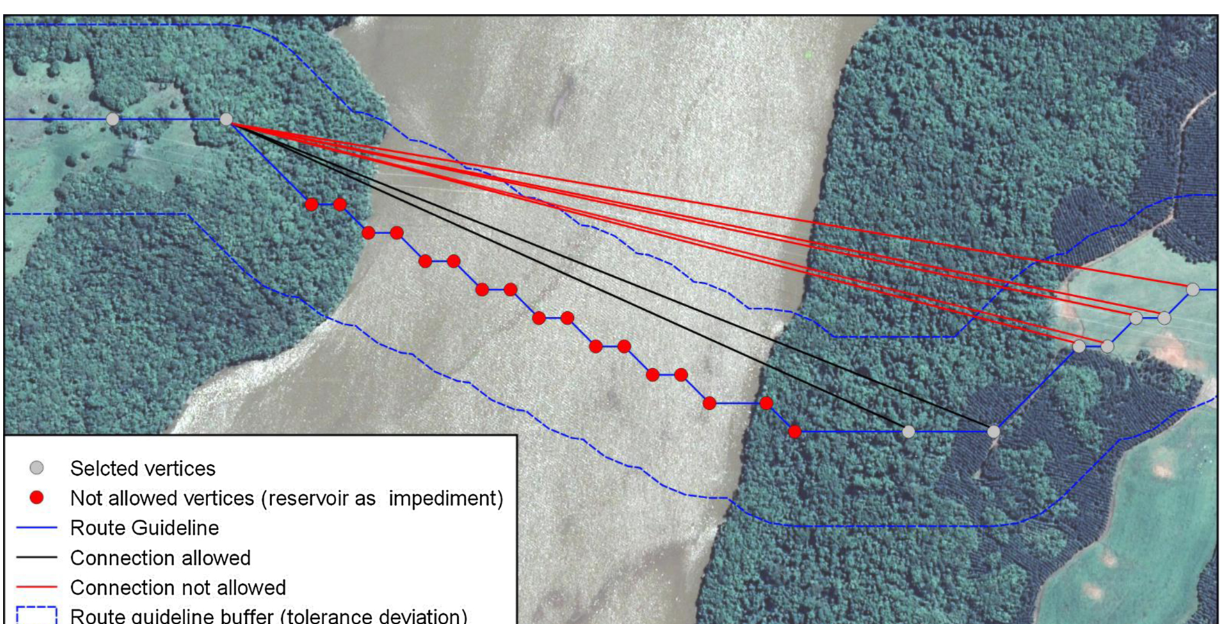

Fig. 3. Example of point selection along the route guideline and the connections between vertices.

an adjacent edge, (2b) requires that only one edge reaches the sink, (2c) requires that at most one edge is active between nodes i and j and (2d) provides non-negativity for decision variables. The total cost (C_{Total}) is calculated by applying the Dijkstra's shortest path algorithm [32]. The result obtained corresponds to the subset of the set E^D that represents the lowest cost route for the TL.

3.3. Tower spotting

A DP algorithm was developed for the tower spotting step, considering the study of Ref. [30] as a base reference. This algorithm incorporates different technical and geographical parameters and constraints to find the optimal tower distribution for real sized instances.

The DP tower spotting process aims at locating different types of transmission towers along the topographic profile while satisfying the technical constraints. The inputs of the algorithm can be divided into three groups: (i) TL route, represented as a point list containing information of elevation, slope, land use, geotechnical soil class, route deflection angles, and impediments; (ii) towers and their characteristics: type, minimum and maximum heights, minimum and maximum weight span, maximum average span, foundation and structure costs; (iii) conductor and clearance parameters: weight, tension for maximum and minimum temperatures and vertical clearance distances according to the land use.

From the input data, a set of possibilities for tower configuration is tested and the model chooses the least expensive tower configuration that satisfies the technical constraints imposed on the mathematical model. The towers applied at the beginning and the end of the TL are chosen previously and are not considered in the optimization since these places present restrictions and peculiarities associated with the interconnection with the substation and require specific types of tower. The route vertices (deflection points) are mandatory locations to place a tower, but the tower types, in this case, may vary. In addition, specific crossings, such as rivers and highways, are also mandatory locations.

The mathematical representation of the problem relies on the definition of three test sites, identified by two-dimensional coordinates (x, y). The x coordinate represents the location of the site on the route from the location of the initial tension tower to the location of the terminal tension tower of the TL. The y coordinate represents the information about the total height (quota site + tower height) for each test site. These sites are then represented by the coordinates (x_k, y_k), (x_{k-1}, y_{k-1}), (x_{k-2}, y_{k-2}), which correspond to the specifications of the ahead site, middle site and back site, respectively, as presented in Fig. 4. Therefore, $x_k, x_{k-1}, x_{k-2} \in X$, where X is the set of possible sites to place transmission towers and y_k, y_{k-1}, y_{k-2} is total height to site transmission tower.

The use of three references to sites is a way to obtain the global optimal solution for the problem using DP, once it is necessary to test all the associations with the back site (x_{k-2}) and with the ahead site (x_k) to obtain the best possibility for the middle site (x_{k-1}). The determination of the x-coordinate of the site x_{k-1} is obtained using the coordinate of the site ahead (x_k) minus a step l_k, i.e. $x_{k-1} = x_k - l_k$. The x-coordinate of the back site (x_{k-2}) is obtained in relation to the coordinate of the site

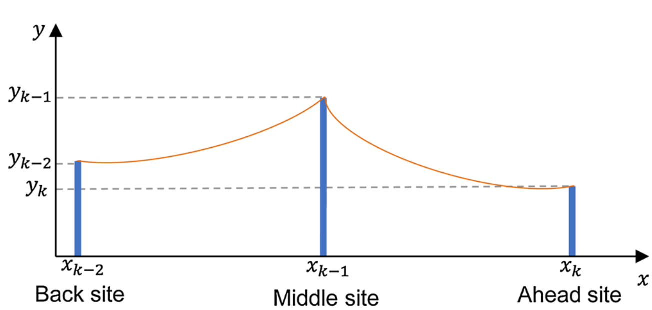

Fig. 4. Representation of test sites.

x_{k-1} minus a step l_{k-1}, i.e. $x_{k-2} = x_{k-1} - l_{k-1}$. Knowing that $l \in L$ represents the set of steps that define the possible distances for a given tower type, it is possible to conclude that by establishing a value for x_k and testing l_k and l_{k-1} the x-coordinates for x_{k-1} and x_{k-2} are obtained. In this way, the entire optimization problem can be structured with respect to the x_k tower.

A general model formulation based on DP for the tower spotting problem is represented by Eq. (3). The objective function represented by $F_k(s_k)$ seeks to minimize the accumulated cost represented by the previous cost $F_{k-1}(s_{k-1})$ defined until location x_{k-1} plus the costs associated with the current location x_k denoted by $C_k(s_k, u_k)$. Where, $s_k = (x_k, x_{k-1}, y_k, y_{k-1})$ which represents the state vector at x_k; u_k represents the decision vector at the same location; N is the total TL length; and $k = 0, 1, 2, ..., N-1, N$, represents the problem stages.

$$F_k(s_k) = \min\{C_k(s_k, u_k) + F_{k-1}(s_{k-1})\} \quad (3)$$

s.t.

$$s_k = m(s_{k-1}, u_{k-1}) \quad (3.a)$$

$$g(s_k, u_k) \geq 0 \quad (3.b)$$

The general form of Eq. (3.a) can be further represented as in Eqs. (4a)–(4d). In such formulation, the state variable s_k will be defined using conditions stored from the previous stage and the current decisions made to satisfy the constraints informed by Eqs. (4a)–(4d). The vector u_k represents the decisions performed at stage k and s_{k-1} represents state variable values defined as parameters (already defined) at stage $k-1$.

$$s_k = m(s_{k-1}, u_k) = \begin{cases} x_k = x_{k-1} + l_k & (4.a) \\ w_k = x_{k-1} & (4.b) \\ y_k = y_{k-1} + h_k & (4.c) \\ z_k = y_{k-1} & (4.d) \end{cases} \quad (4)$$

Eq. (3.b) represents the set of other structural constraints of the model more specifically defined by Eqs. (5a)–(5c). The decision vector at stage k is defined as $u_k = (h_k, l_k, t_k)$, where h_k represents the difference in height from the previous stage, l_k is the length step in the route and t_k is the selected tower type.

$$g(s_k, u_k) = \begin{cases} \dfrac{l_k + l_{k-1}}{2} \leq MAS_{t_k} & (5.a) \\ \underline{WS_{t_k}} \leq \dfrac{l_k + l_{k-1}}{2} - c\left[\dfrac{h_k}{l_k} - \dfrac{h_{k-1}}{l_{k-1}}\right] \leq \overline{WS_t k} & (5.b) \\ d_{min} \leq y_k + h_k + \dfrac{(x_k + l_k - x')^2}{2 \times c} - (x_k + l_k - x') & (5.c) \\ \quad * \left(\dfrac{l_k}{2 \times c} - \dfrac{h_k}{l_k}\right), \ \forall\ (x_k \leq x' \leq x_{k+1}) & \end{cases} \quad (5)$$

Eqs. (5.a) and (5.b) represent the physical efforts from the wire weight and Eq. (5.c) represents the electrical safety heights that need to be satisfied to reduce the chance of potential faults (e.g. short circuits) in the TL. By respecting the physical and safety criteria the model defines decisions with respect to the distance between the allocation of each tower, that is, relative values represented by the average span and weight span limits specified for each tower type $t_k \in T$. The enforcement of the minimum height for each position in the TL is ensured by d_{min}, because the height of the conductor is directly connected to the total height of the tower. The constant c represented in Eqs. (5.b) and (5.c) is associated with the wire characteristics considered in the TL. Constraint (5.a) verifies if l_k and l_{k-1} form an average span smaller than the limite average maximum span defined by $MAS_t k$ for tower type t_k. Moreover, Eq. (5.a) is directly related to the horizontal efforts created by the cables in the towers. Constraint (5.b) enforces that the height difference between the towers located at (x_k, x_{k-1} e x_{k-2}) and the size of the associated step lengths (l_k e l_{k-1}) form a weight span between then minimum ($\underline{WS_{t_k}}$) and maximum ($\overline{WS_t k}$) for tower type t_k. This constraint is directly related to the vertical efforts that the wires cause to the towers. Thus, by verifying the vertical and horizontal efforts of a tower, the model is instinctively checking its span. As there are several types of towers ($t \in T$) and each type supports different $MAS_t k$, $\underline{WS_{t_k}}$ e $\overline{WS_t k}$ all the possibilities have to be verified by the model. Constraint (5.c) check that the cables are at a safe distance from the ground, so that at all points defined using l_k the wire height should be higher than (d_{min}). Here, x' corresponds to each existent point between x_k and x_{k+1}, for which d_{min} has to be enforced.

4. Case study

The 525 kV TL Machadinho – Campos Novos, selected as a case study, is a single circuit TL with approximately 40 km that connects the Hydropower Machadinho to the substation of Campos Novos, both located in Santa Catarina state, Brazil. The region is characterized by smooth topography plateaus and edges with dissected valleys with high slopes. The geotechnical conditions are favourable and relatively homogeneous, which reflected in a small variability in the design of foundations, with the occurrence of only one special foundation applied for low resistance soils. Due to the technical complexities of the initial stretch of this TL, regarding the proximity to the Machadinho hydropower dam and the reservoir, the methodology was applied from the first tower after the reservoir to the Campos Novos substation (Fig. 5). All technical information for Machadinho – Campos Novos TL used in the case study was obtained from the design documents provided by the TBE Transmission Company, which is the owner of this TL. The tower types applied and their characteristics are shown in Table 1. The costs were originally estimated in Real (Brazilian currency) and converted to US Dollar considering an exchange rate of 4.20 (average rate for September 2018). The computational resources used to perform the tests were a standard personal desktop with a 3.40 GHz Intel i7-2600 processor and 32GB of RAM. For the routing guideline definition, tools of QGIS software were used. On the other hand, the vertex siting and tower spotting methodology were implemented as software using the programming language “C”.

4.1. Route guideline definition

The cost surface representing the spatial distribution of the implementation costs of the study area was determined based on four geographical criteria (Fig. 6). The spatial resolution of the cost surface and the raster surfaces of each geographical criterion is 30 m. The preservation areas map consists of permanent preservation areas [34] and conservation units [35]. The land use map was generated using supervised classification of Landsat 5 images. The High Erosion Potential Areas (HEPA) is defined as areas where the Natural Erosion Potential [36] is higher than 750. The Roads Density were calculated using a road map from *OpenStreetMap* project (https://www.openstreetmap.org/). The costs related to each geographical criterion as well as the Base Cost (Table 2) were estimated based on the price database from the Transmission Budget Methodology [31]. The cost surface components were selected based on the study area characteristics, with a focus on the implementation costs of the TL selected for the case study. However, the methodology allows other costs to be included as a component of the cost surface. For example, additional costs (for implementation and operation of the TL) associated with lightning discharge and insulation problems can be included if maps of soil resistivity and ceraunic index are available.

4.2. Vertex siting

The vertex siting was performed considering the same towers of the Machadinho - Campos Novos 525 kV TL design (Table 1). For each

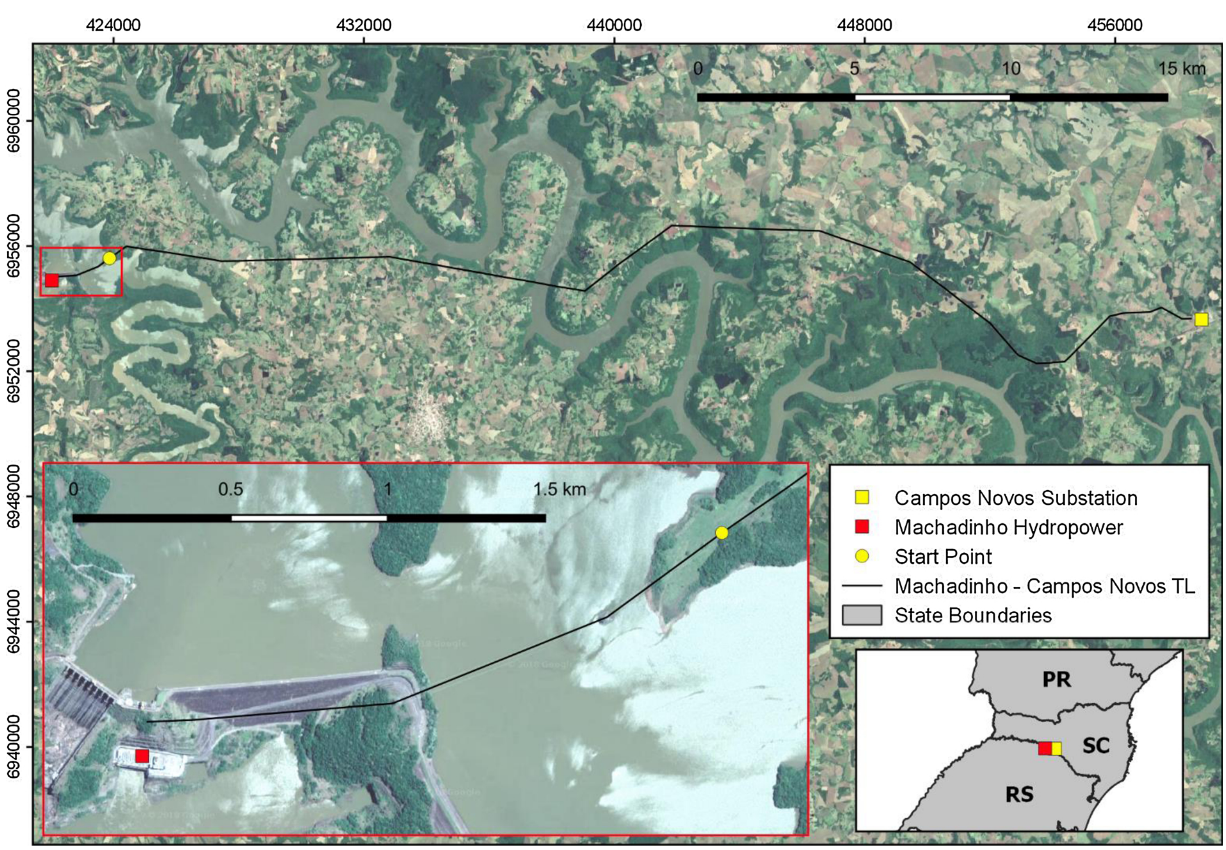

Fig. 5. Machadinho – Campos Novos TL.

Table 1
Tower parameters and costs of Machadinho - Campo Novos TL.

Tower	Application [%]	Heights - h [m]			MD [°]	MAS [m]	WS [m]		SC = a.h + b [US$]		FC [US$]
		Min.	Max.	AV			Min.	Max.	a	b	
SS – Suspension	33	17.5	35.5	29	3	450	300	600	655	8,634	11,580
SR – Reinforced suspension	28	17.5	44.5	37	3	560	300	700	752	7,304	15,336
SA – Angle suspension	13	17.5	44.5	35	10	700	350	850	846	7737	19,627
AM - Anchor	14	17.5	52	30	25	1,000	−300	1,120	1,507	39,391	24,736
AT – Dead-end anchor	12	17.5	47.5	33	56	1,400	−300	1,300	1,678	43,369	30,881

AV: average heights of towers, estimated from the occurrence in the TL design; MD: maximum deflection; MAS: maximum average span; WS: weight span; SC = a.h + b: structure cost equation, where SC is the structure cost, *h* is the tower height, *a* and *b* are equation parameters; FC: foundations cost, estimated as an average cost of the design foundations of the TL. The costs of towers and foundations were estimated based on design characteristics and the price database from the Transmission Budget Methodology [31].

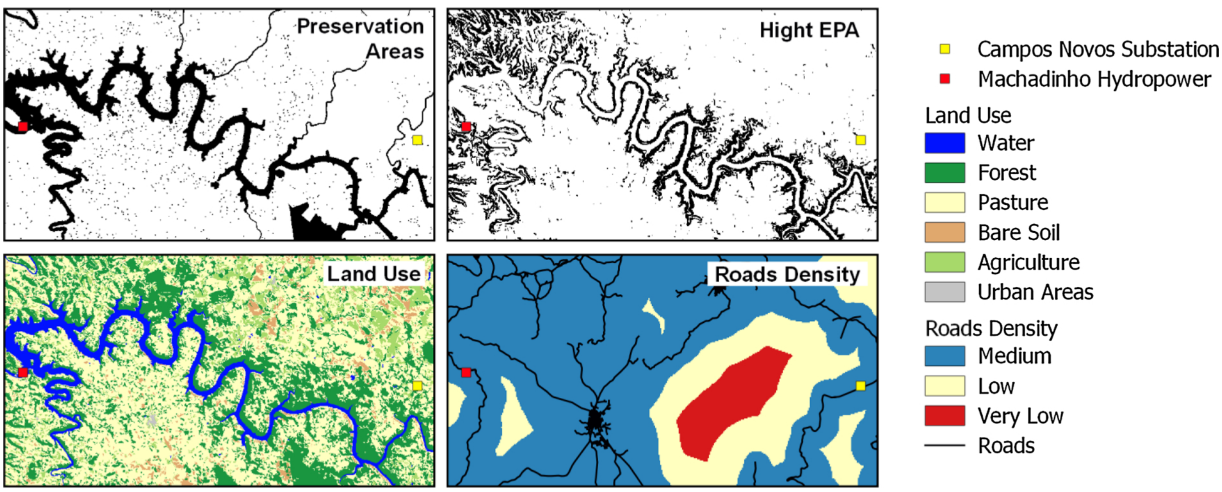

Fig. 6. Geographical criteria selected to compose the cost surface of 525 kV Machadinho – Campos Novos case study.

Table 2
Cost surface components of LT 525 kV Machadinho – Campos Novos case study.

Cost group	Component	Geographical criteria	Class	Cost [US$/km]
Base cost	Conductors, earth wire, grounding, topography, and geotechnical survey.	n.a.	n.a.	128,285
	Structures (1)	n.a.	n.a.	129,669
Structural additional costs	Additional costs for preservation areas (2)	Preservation areas (APPs e UCs)	–	19,858
	Additional costs for high erosion potential areas (EPA) (3)	High erosion potential areas (EPA)	–	3,731
	Additional costs for rivers (4)	Reservoir (from land use criterion)	< 400 m (5)	19,858
			400–600 m	34,811
			> 600m	94,622
Right-of-Way Costs	Landowner compensation, cleaning, deforestation and reforest compensation costs	Land use	Water (5)	29,971
			Agriculture	17,564
			Urban areas	Impediment
			Forest	29,971
			Pasture	8,771
			Bare soil	16,254
	Costs to open new access to equipment mobilization and material delivery	Roads density	Medium	2,117
			Low	2,647
			Very low	3,176

(1) The structures cost estimated considering an average span of 478 m, average height of 29 m, and application percentage of the TL design (Table 1).
(2) The additional cost for preservation areas was estimated considering towers 10 m higher in order to avoid forest suppression.
(3) The additional cost for high erosion potential areas was estimated considering foundations 10% more expensive than the usual.
(4). The additional costs to cross the reservoir were estimated considering structures 10% more expensive for sections of 400–600 m width and 20% for sections of more than 600 m width. The cost estimate was performed considering the use of reinforced structures in order to improve the security of the crossing sections.
(5) There are no structural additional costs to cross the reservoir sections with a width smaller than 400 m. However, the cost value adopted is the same as structural additional costs for preservation areas, in order to avoid that this width class became a preferential area for the least-cost path algorithm. The same situation occurs for the water class of right-of-way costs. In this case, the value used for the water class was the values of forest areas.

tower the following parameters were used: average height (to calculate the cost of each structure), foundation cost, and maximum deflection angle supported. A value of 222,473 US$/km was adopted as the cost of the edges. This value corresponds to the base cost (Table 2) recalculated considering only towers SS, SR and SA, since the towers AT and AM are mainly applied for deflection points, which will be determined in this step. A value of 100 m was adopted as the deviation tolerance of the route guideline (100 m from each side of the route, resulting in a total of 200 m corridor width).

In order to define the set of vertices $A \in G$, points along the route guideline were sampled considering an average distance of 120 m. In this sampling process, the reservoir of the Machadinho hydropower plant and its affluent drains were considered as prohibited locales to place a vertex. Bottomlands were also considered as impediments, as they are sites associated with a complex relief and low resistance soils.

4.3. Tower spotting

As well as for the vertex siting step, the tower spotting was performed considering the same family of towers used in the executive TL design, wherein the technical parameters and costs are presented in Table 1. For slopes in the intervals of 20–30° and 30–40°, a cost factor of 10 and 50%, respectively, were considered to represent new cost adders for the TL design. On the other hand, places with a slope greater than 40° were considered as prohibited to place towers. For the heights of the towers, an increase of 5 m was used, considering the minimum and maximum limits (Table 1), adjusted for the height step of 5 m. For example, the minimum limits was adjusted from 17.5 to 15 m. For modelling the TL wire's curve, the parameters adopted were: 1944 and 2199 kgf for horizontal wire tension (considering a 60 °C as the maximum wire's temperature and −6 °C as the minimum, according to the executive TL design) and 1.6 kgf/m for the wire's weight. The conductor considered was the ACSR Rail of 954 AWG size. Vertical clearance values for each land use class were determined considering NBR5422 [37]: 8.5 m for water, forest and pasture, 9 m for agriculture and 10.5 for streets and avenues.

In order to construct the topographic profile of the route, a mean resolution of 30 m was used, i.e, the tracing of the TL was divided into equally spaced points of 30 m. The land use along the route was determined from the land use map generated in the "route guideline definition" step. Crossings of streets and avenues were identified from high-resolution satellite images available on Google Earth. The elevation and slope data were obtained from the *WorldDEM* digital elevation model with a spatial resolution of 12 m and absolute vertical precision of fewer than 10 m.

5. Results and discussions

The methodology proposed for TL routing and tower spotting was capable to provide cost savings of 14% for the case study and details about the results obtained are presented in the items 5.1 and 5.2. In relation to the computing time, the routing guideline methodology, based on QGIS raster routing tools, ran reasonably fast. Most of the time is spent in the steps of pre-processing geographical data for the cost surface construction. The vertex siting and tower spotting algorithms (implemented using the programming language "C") ran in about five minutes for the case study, which can be considered a reasonable running time given the great number of restrictions and complexity of the problem.

5.1. Route guideline definition and vertex siting

The modelled routes resulted from the methodology (the route guideline, resulted from the first step of the methodology, the route guideline definition and the vertex siting route, resulted from the vertex siting step) were compared with the real TL route (525 kV Machadinho – Campos Novos TL) in relation to the total length, number of vertices and implementation costs (Table 3). The implementation costs presented in this section were estimated based only on the cost surface generated in the Route Guideline step. As exposed in item 4.1, the base cost is estimated considering a proportion of towers, average span and average tower height. This way, the costs presented in Table 3 does not reflect directly the number of vertices of each route but rather an average cost based on a fixed number of anchor towers defined as a parameter of the cost surface. Two main aspects can justify this approach adopted to estimate the costs of the routes in this step: (i) the tower type applied for a vertex is chosen not only according to the deflection angle but also according to other criteria such as wind and weight span, which will be defined only in the tower spotting step; (ii) the excessive vertex number of the route guideline does not represent a real TL route, technically speaking. Therefore, if the vertex number is considered to estimate the costs, the total cost of the route guideline would not be directly comparable with the other routes.

The modelled routes presented smaller length and implementation costs than the real TL route. In the original design (real TL route), the decision maker preferred to avoid two reservoir crossings, resulting in a longer route. However, the modelled routes presented a more linear shape and crossed the reservoir in three points. The average width crossing sections are 500 m, which does not show any technical restriction given the towers adopted in the TL design. In addition, the real TL route presents a great deviation near the Campos Novos substation, which helps to explain the greater length. This deviation was not explained by the geographical criteria selected to compose the cost surface, but a possible explanation could be a landowner conflict identified during TL design. The vertex siting methodology was able to reduce the number of vertices of the route guideline from 127 to 9, where the distortions of the route guideline were rectified, resulting in a straighter and shorter route (Table 3 and Fig. 7).

5.2. Tower spotting

The tower spotting methodology was applied over two routes: (i) the real route of Machadinho – Campos Novos TL, which allowed the evaluation of the tower spotting methodology individually, by comparing the results with the real TL design (Fig. 8); (ii) the route resulting from the vertex siting methodology, which allowed to evaluate the proposed methodology as a whole, integrating the route guideline definition, vertex siting and tower spotting.

Table 4 shows the number of towers, average height, average span and tower costs for the real design TL and for the results obtained with the tower spotting methodology. Even though the tower spotting over the real TL route presented a greater number of towers when compared with the TL design, the tower spotting methodology was able to reduce the structures and foundation costs by 4.2%. Considering the total cost (including conductors and Right-of-Way Costs), the cost reduction is 1.96% for the tower spotting over the real TL route. For the integrated methodology (tower spotting over the route resulted from the vertex sitting step), the cost savings are even greater since the modelled route has a smaller length. Considering only the structures and foundations, the cost saving is 25%, and for the total cost (including conductors and Right-of-Way Costs), the cost reduction is 14%.

6. Conclusions

This paper presents a novel methodology for TL routing and tower spotting, focused on decision making support for transmission auctions, TL planning and design. The methodology developed was applied to analyze the 525 kV Machadinho – Campos Novos TL and the results were compared with the real TL design.

The combination of route guideline definition and vertex siting shows reasonable results. The route generated presented a smaller length and implementation cost than the real TL route and showed technical consistency, mainly in relation to the vertex number and the reservoir crossings. The vertex siting brings an important contribution as an alternative to post-process and rectify the distortions of routes generated from traditional raster-based least-cost path approach. In addition, the deflection angle is incorporated in the optimization, which contributes to generating a route technically reasonable in relation to the number of vertex and their positions along the route.

The results of the tower spotting methodology show cost savings of

Table 3
Implementation costs for the modelled routes and design route estimated from the cost surface.

Route	Length [m]	Vertex number	Implementation cost [US$][1]	Cost reduction
Route guideline	35,513	127	9,865,751	4.72%
Vertex siting route	34,915	9	9,811,725	5.24%
Real TL route	37,568	20	10,354,256	–

[1] Costs estimated from cost surface (see Table 2), which corresponds to structural, foundations and Right-of-Way Costs.

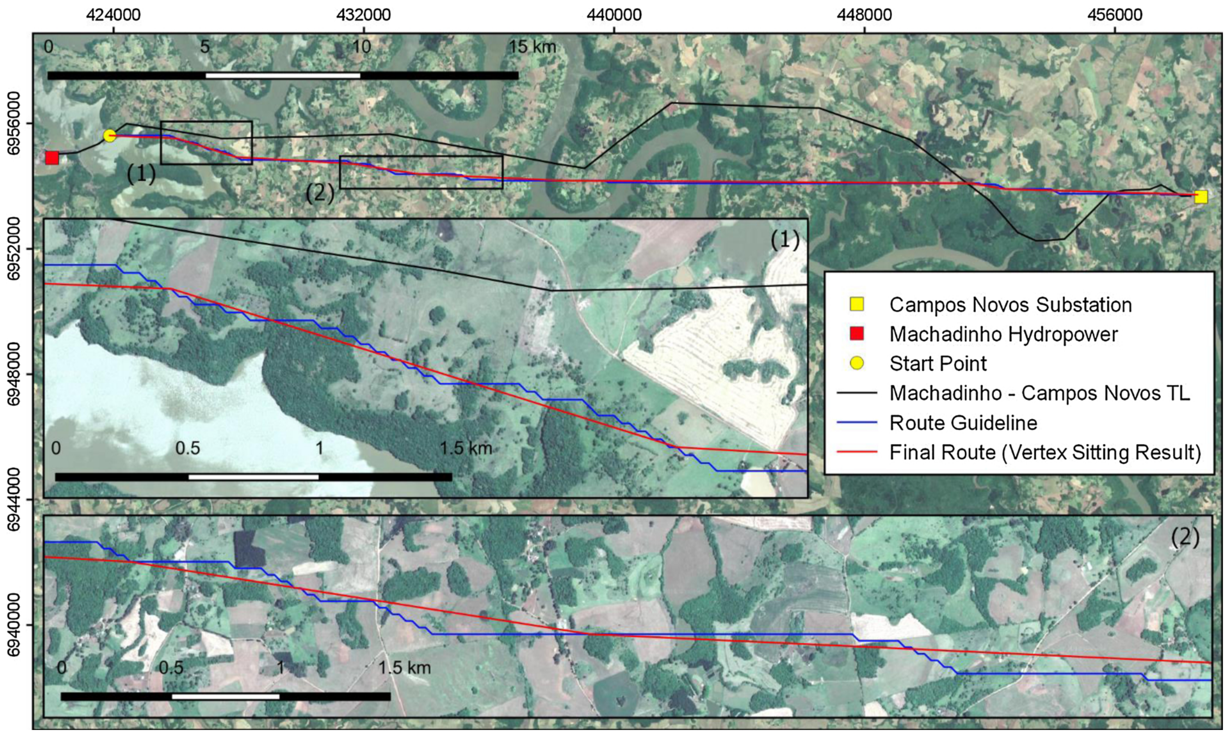

Fig. 7. Geographical representation of the route guideline and final route (vertex siting result).

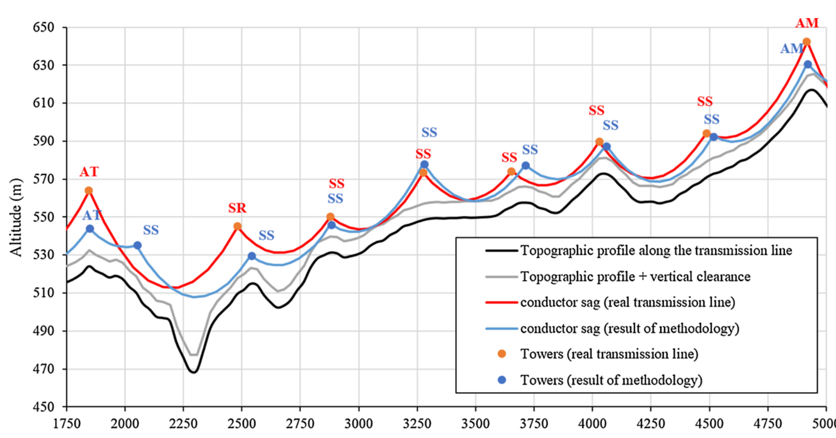

Fig. 8. Tower spotting results over the topography profile for a stretch of the TL route.

4.2% for structures and foundations compared to the real TL design. Several constraints and criteria are considered in the optimization, such as different types and heights of towers, wind span, weight span, deflection angle, admissible slope and admissible clearance for different land use classes. The integrated methodology (route guideline definition, vertex siting, and tower spotting) generates a cost saving of 14% with respect to the real TL design, which is even greater than the cost saving considering only the tower spotting step. It is important to highlight here that the methodology prosed were developed and applied for the study case due to simplification assumptions and using geographical information not detailed enough for an executive design. The topography, for example, has a spatial resolution of 12 m with a vertical precision of fewer than 10 m; the land use map used has a resolution of 30 m; the tower heights adopted vary by 5 m, while for an executive design it varies by 1–1.5 m. Therefore, the methodology should be applied carefully for preliminary planning of new transmission lines, which the final feasibility of the TL project should be evaluated with detailed information in later steps.

Table 4
Results of the tower spotting methodology over the modelled route (vertex siting result) and over the real route of 525 kV Machadinho – Campos Novos TL.

Tower	Tower spotting over the modelled route (vertex siting result)			Tower spotting over the real TL route (design route)			Real tower distribution (design)		
	No	AH [m]	Cost [R$]	No	AH [m]	Cost [US$]	No	AH [m]	Cost [US$]
SS	45	22	1,570,617	36	24	1,301,173	27	24	967,524
SR	20	27	858,866	22	29	979,344	23	32	1,069,287
SA	11	28	571,198	8	34	451,636	11	30	575,618
AM	3	20	282,799	7	23	690,004	9	31	995,326
AT	2	35	265,974	10	22	1,103,316	9	30	1,116,332
Total	81	25	3,549,454	83	26	4,525,473	79	28	4,724,086
Difference	−2	3	1,174,632 (25%)	−4	2	198,613 (4.2%)	–	–	–
Total Cost	8,703,870			9,947,543			10,146,156		
Cost Saving	1,442,286 (14.22%)			198,613 (1.96%)			–		

No: number of towers applied; AH: average height of towers; total: represent the average height of towers and the total cost and number of towers; difference: represents the difference of the total values between tower spotting results and TL design; total cost: represent the structures and foundations costs (tower spotting results) plus the Conductors, earth wire, grounding, topography, geotechnical survey and Right-of-Way Costs, calculated from the cost surface; cost saving: represents the total cost savings in relation the total cost of the TL design.

In addition, even though the results of the case study show least cost alternatives for the TL design, there is no acceptable margin of error for planning an LT in the auction phase, when several design alternatives, with different implementation costs, can be considered. It is important that the transmission line has a lower cost than the maximum revenue indicated in the auction considering the Brazilian context. Therefore, the lower the cost of implementing the alternative identified by the company, the greater the competitive power in the auction. In addition, better knowledge of the characteristics of the transmission line design (layout, towers and applied foundations) allows the company to have better estimates of the total cost of implementation, reducing financial risks.

In relation to the environmental restrictions presented in the study case, it is important to highlight that the methodology allows for several other criteria to be incorporated, such as indigenous areas, protected areas, mining, archaeology, and other land aspects. In this work, the optimization goal was to minimize the cost of the TL implementation, so the weights of the criteria were defined as the implementation costs. However, other costs not considered in the case study presented in this paper can be integrated into the methodology, such as operation and maintenance costs, eventual costs due to lightening discharges and insulations problems. Also, some costs considered as constant for the entire study area can be related to some geographical criteria, such as grounding costs, which could be related to the soil and geological conditions. In addition, the methodology allows different ways of weighing the criteria following different objectives. For example, weights may be associated with environmental impacts of the route or with risk reduction to the TL project. This flexibility increases the applicability of the proposed methodology, especially for preliminary phases of TL planning, where different alternatives can be evaluated.

In relation to the computational requirements, the methodology has no restrictions and was tested using a standard personal desktop. Most of the time necessary to apply the methodology is related to the data processing step, and the optimization algorithms take about five minutes each to run. The capacity to optimize the implementation costs of a TL, with computational efficiency and detailed technical modelling, makes the methodology proposed a powerful tool for decision making in transmission auctions, and also can be used as an auxiliary tool for planning and design of transmission lines.

Finally, we suggest for future studies the application of the methodology proposed considering a multi-objective approach, where environmental impacts and operational risks can be considered together with the implementation costs for the selection of the best design alternative for a new transmission line. The methodology proposed can be applied integrated with the methodology proposed by Ref. [38] in order to support the analysis and periodization of new transmission lines in transmission auctions. In addition, new case studies should be evaluated considering other costs and constraints not explored in the case study presented in this paper, such as operational and maintenance costs, insulation problems due to pollution, lightening incidence and grounding problems due to soil conditions.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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