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Generating Alternative Transmission Line Routes: A Balanced Approach to Technical and Socio-Environmental Criteria

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***Abstract*—Transmission line routing plays a crucial role in the planning and development of electricity transmission infrastructure. Traditional approaches to route selection often concentrate on single routes, potentially overlooking optimal solutions and not fully capturing the complexities and trade-offs inherent in the process. In this paper, we propose a novel methodology for generating optimal alternatives of transmission line routes, designed to provide realistic options for decision-makers in real-life transmission planning studies. Our approach integrates advanced optimization techniques with geographic information systems (GIS) and multi-criteria decision analysis (MCDA) to systematically explore and evaluate route alternatives based on technical, environmental, social, and economic criteria. By generating a diverse set of realistic routes, the methodology enables decision-makers to make informed choices that balance competing objectives and the interests of stakeholders. Through a case study in Chile, we demonstrate the ability of the proposed methodology to produce route alternatives that meet technical requirements while minimizing socio-environmental impacts. By offering a comprehensive set of options, this methodology supports stakeholders in selecting routes that fulfill infrastructure needs while addressing societal and environmental concerns.**

***Index Terms*—transmission line, routing, GIS, optimal routes, socio-environmental criteria, technical criteria**

1 Introduction

1.1 Motivation

The global transition toward decarbonization necessitates the extensive deployment of renewable energy sources, which are often located far from consumption centers [1], [2]. Consequently, achieving this goal requires the expansion of transmission network infrastructure to bridge these geographical gaps [1]. Transmission lines inherently interact with the territory they traverse, creating socio-environmental impacts and influencing a broad spectrum of stakeholders [3]. This interaction often generates tension between the societal benefits of clean energy integration and the localized disruptions caused by new infrastructure development [4].

Conflicting objectives are a significant source of delays in transmission projects worldwide, stemming from opposition by affected communities and other stakeholders [5], [6]. For instance, in Germany, resistance from local communities has delayed the construction of high-voltage direct current (HVDC) lines crucial for connecting wind-rich northern regions with the energy-intensive south [7]. Similarly, in Chile, the Cardones-Polpaico transmission project faced substantial delays due to opposition from indigenous communities and environmental groups, resulting in costly project postponements [8]. These cases highlight the critical need to reconcile technical and socio-environmental considerations to ensure timely project execution [4].

To address these challenges, the planning and routing of transmission lines must account for both technical and non-technical criteria [2]. Technical considerations include terrain characteristics, construction feasibility, and system reliability [1], [9], while non-technical factors encompass environmental preservation, societal acceptance, and economic costs [3], [10]. Integrating these diverse criteria into a decision-making framework is essential for identifying optimal transmission line routes that minimize impacts while balancing the needs of all stakeholders [4]. This holistic approach not only enhances project feasibility but also facilitates stakeholder engagement, fostering smoother project development in complex socio-environmental contexts [2], [3].

1.2 Literature review

Several methods and mathematical models have been developed to address the complexities of transmission line routing, aiming to identify optimal solutions for transmission planning challenges. Advanced siting and routing methodologies, such as EPRI-GTC [11], ERPA [12], OPTIPOL [13], and The Holford Rules [14], provide tools for minimizing land-use conflicts and addressing societal concerns. These approaches leverage Geographic Information Systems (GIS) to evaluate key factors such as terrain costs, slopes, obstacles, infrastructure, and maintenance requirements. By systematically integrating this data, these methods offer a structured way to tackle the challenges of route optimization [4], [15].

An important focus of routing methodologies is the avoidance of costly terrains, obstacles, and other constraints [15]. For instance, Monteiro et al. [15] introduced the concept of Global Potential Observation Hours (GPOH)—a metric representing the daily visibility of transmission towers—as a cost factor to minimize visual impacts. Beyond visibility, other works have incorporated factors such as slope, landslides, road crossings, ice zones, proximity to national parks, archaeological sites, residential areas, forests, and river crossings to ensure comprehensive route evaluations [16], [17].

Innovative approaches have also explored the integration of specialized tools to refine routing decisions. For example, Li et al. [18] employed the Lightning Location System (LLS) to reduce lightning strike exposure and enhance system protection, while [19] combined multiple criteria—cost, visibility, population density, and ecosystem naturalness—to optimize routes. Santos et al. [2] further emphasized the integration of geographical, engineering, and cost considerations to support the decision-making process for overhead transmission line design. Similarly, environmental factors such as terrain slope and maintenance costs have been incorporated to enhance route sustainability [15].

Artificial intelligence techniques have emerged as powerful tools in transmission routing, enabling more adaptive and efficient decision-making. For instance, [20] applied Q-learning to dynamically identify optimal paths through a trial-and-error process guided by expert-defined criteria. Complementing these approaches, multi-criteria decision-making methods, such as the Analytic Hierarchy Process (AHP) and its fuzzy variant (FAHP), have been used to weigh relevant factors for routing decisions [16]. Moreover, mixed-integer linear programming (MILP) has been proposed by [21] to enhance computational efficiency by refining constraints and simplifying models. This technique has proven particularly useful for transmission expansion planning, as demonstrated by Matamala et al. [22], who integrated socio-environmental externalities to reduce conflicts and improve decision-making.

Beyond artificial intelligence, algorithms adapted from other fields have also shown potential in optimizing transmission routing. The Rapidly-Exploring Random Trees (RRT) algorithm, originally developed for robotic motion planning, was adapted by Gonçalves et al. [3] to identify efficient transmission line routes. Its ability to narrow search areas while maintaining computational efficiency makes it a valuable tool, though robust heuristics are needed to estimate optimal costs. Similarly, Dynamic Programming (DP) models have been applied to route optimization, as highlighted by [15]. Additionally, [2] employed Dijkstra's algorithm to construct realistic routes by reducing distortions and minimizing costs within predefined corridors. Dijkstra's algorithm, widely recognized for its efficiency in finding shortest paths, has become a cornerstone of transmission routing research [4], [18], [19], [23].

A recurring theme across these methodologies is the emphasis on evaluating and balancing multiple criteria to generate optimal route alternatives. For instance, studies such as [4], [15], [18], [20], [21] have utilized raster analyses to integrate diverse considerations, such as land-use priorities, environmental constraints, and engineering requirements, into the decision-making process. Furthermore, [19] underscored the sensitivity of transmission paths to the positioning of start and end points, noting that even minor adjustments can lead to significantly different routes and impacts. Incorporating socio-environmental considerations early in the planning process, as demonstrated by Matamala et al. [9], [22], has been shown to substantially reduce land-use conflicts and enhance project feasibility.

In real-world applications, like in Chile, transmission planning has traditionally prioritized economic and reliability objectives, often overlooking land-use and environmental concerns [24]. To address these shortcomings, the Chilean Energy Ministry developed a methodology integrating environmental sustainability into transmission system planning [25]. By fostering early stakeholder engagement, this approach not only reduces risks but also ensures that proposed routes are socially acceptable and environmentally considerate.

While existing methodologies provide effective frameworks for transmission line routing, they primarily focus on generating a route solution rather than offering structured decision-making tools for, first, generating alternative routes that balance trade-offs between multiple objectives, and second, comparing these solutions from a least regret viewpoint. So far, existing approaches optimize a single function or apply predefined weightings, limiting their adaptability to diverse stakeholder preferences. Additionally, current methods lack a systematic framework for comparing route alternatives beyond cost-based rankings. To address these gaps, this study introduces a regret-based decision-making approach, allowing a structured comparison of routes by quantifying the trade-offs between different objective functions. The following section details the contributions of this work, emphasizing its role in generating diverse route alternatives and providing a structured method for prioritizing solutions that balance technical, environmental, and socio-economic considerations.

1.3 Contribution

This work aims to integrate a diverse array of viewpoints—technical, environmental, social, and economic criteria—into the transmission line route selection process. By generating a set of realistic route alternatives, the methodology represents the interests of various stakeholders, providing valuable insights to inform and support the decision-making process.

Our methodology generates alternative routes via a novel mathematical framework that integrates advanced optimization techniques with geographic information systems (GIS) and multi-criteria decision analysis (MCDA). This framework systematically generates route alternatives, balancing competing criteria to ensure technically robust and socio-environmentally considerate solutions, and compares these alternatives via least-regret analysis.

The core contribution of this work is that the methodology incorporates a Regret Matrix, which enables the comparative assessment of route alternatives across multiple objective functions. This structured approach evaluates trade-offs using criteria such as minimum-average and minimum-maximum regret, providing quantitative insights into the relative advantages of each alternative. By applying this matrix, decision-makers can identify the most advantageous route that aligns with stakeholder priorities and minimizes impacts.

Through a practical application in a real-world case study, we demonstrate the methodology's capability to identify route characteristics aligned with the needs and preferences of informed decision-makers. This approach offers a comprehensive toolkit for route selection, promoting a balanced and inclusive decision-making process that aligns with technical feasibility, environmental sustainability, and societal acceptance.

1.4 Paper structure

This paper is organized as follows. Section 2 presents the methodology and the optimization problem (which is presented in detail in the A). Section 3 introduces the case study, including the input data of the area. Section 4 presents the results related to the generated alternative routes. Finally, section 5 presents the conclusions.

2 Methodology for routing alternative paths

2.1 General description

The proposed methodology systematically generates optimal routes by integrating technical and non-technical criteria, including environmental, social and economic factors. The process begins by representing weighted maps of prohibitive zones, such as national parks, urban areas, and terrain features like elevation and slope, using raster images (step 1 in Figure 1). Rasterized data play a crucial role in penalizing specific land uses, ensuring that the routing process avoids areas with high socio-environmental or technical constraints. Subsequently, the rasterized data are transformed into a spatially structured network of nodes (step 2 in Figure 1), which forms the basis for solving the optimization problem. A mathematical model combines socio-environmental and technical criteria to determine the least-weighted paths by adjusting parameters to reflect the relative importance of each criterion (step 3 in Figure 1). This optimization framework employs Dijkstra's algorithm to efficiently identify a diverse set of potential routes, each optimized for a unique combination of criteria. To improve the interpretability and usability of the results, the generated routes are clustered based on their geographical proximity using classification methods, enabling the identification of representative routes within each cluster (step 4 in Figure 1). Subsequently, these representative routes are refined through a smoothing process to minimize zigzagging and angular breaks, resulting in straighter sections that better reflect realistic transmission line placement (step 5 in Figure 1). By producing a variety of route alternatives, the methodology provides decision-makers with a comprehensive menu of options that balance competing objectives. This approach not only accommodates diverse stakeholder requirements but also supports informed decision-making, ensuring technically feasible, environmentally considerate, and socially acceptable solutions.

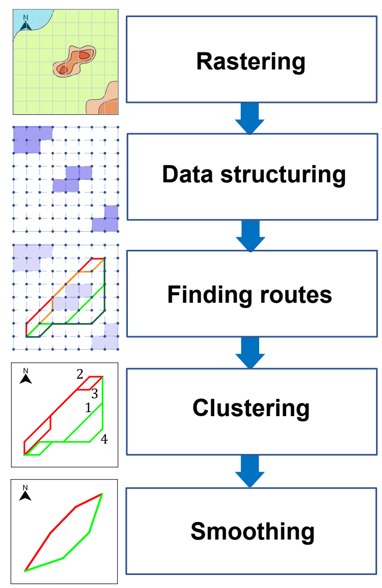

Fig. 1. General diagram of the methodology.

2.2 Rasterization

The rasterization process creates a matrix of cells, where each cell represents a unit of area with specific dimensions and reflects an alternative land use that is valuable to society [4]. Due to alternative land uses, areas of high social and environmental impact can be identified using images or polygons containing geographical information. These areas of interest may or may not be suitable for the positioning of the transmission line. Each externality associated with land use can be incorporated into a composite image, which results from overlaying multiple geographic layers. The composite image is then rasterized to form a data structure that associates the weighted land value with the geographic location of the land.

For rasterization, defining the study area where the transmission line will be located is essential. The study area is a space of significant size that allows for many potential corridors to identify alternative routes to avoid complications arising from the collection of information at the local level [25]. The size of the Study Area used in the present work is defined by a rectangle whose dimensions envelop the transmission lines endpoints, considering a margin from 3 to 5 km from the ends. The endpoints of the transmission line are defined a priori by the planning entity, which establishes the new transmission expansion projects.

To consider geographic data within the study area, the information was expressed through polygons that represent land uses such as national parks, bodies of water, urbanized areas, cultural heritage areas, etc. In this sense, QGIS [26] was used to handle and convert the area of the polygons into raster format images. Additionally, the Python programming language [27] was used to transform layers and serve as the computational engine for raster operations through specialized tools from The Geospatial Data Abstraction Library (GDAL) [28] and GeoPandas [29]. To generate a fully weighted map, attributes were assigned based on the weightings defined in sections 2.2.1 and 2.2.2.

2.2.1 *Socio-environmental criteria*

This section considers several areas of value to society and the environment, each assigned a specific weighting. These weightings are selected according to the geographical characteristics of the study area [2]. Each criterion's weighting was estimated based on data from the Chilean fringe study methodology for new transmission lines [25]. Consequently, prohibitive areas receive high weightings and must be avoided, such as national parks, urban areas, areas of cultural interest, and water bodies in a given area. To quantify the preference for transmission line placement, each raster map was transformed to a common scale ranging from 4 (most preferred) to 100 (prohibitive). These values represent low and high impact, respectively.

Table I presents the weightings assigned to the different criteria used in this study. In the same way, distance buffer zones were established around each criterion of interest to minimize the impact of the transmission line route passing in the vicinity of the prohibitive areas. The weights related to each criterion were estimated based on penalty data from the methodology used by EPRI-GTC [11] and by the Study for the Implementation of the Preliminary Fringe Determination Process [25].

In Table I, the road network is assigned the lowest weight, meaning that, from a mathematical optimization perspective, roads are considered the most preferable option for transmission line routing. This does not imply a purely social or economic preference but rather a result derived from the weighting methodology used. Additionally, categories such as agricultural areas, forests, and other land types should align with the regulatory framework applicable to each specific case study. The classification of Open Field in this work corresponds to areas that are not subject to significant restrictions for transmission line placement.

TABLE I
WEIGHTINGS OF SOCIO-ENVIRONMENTAL CRITERIA, WHERE THE HIGHEST VALUE MEANS PROHIBITIVE, AND A LOWER VALUE GIVES PREFERENCE TO POSITIONING THE TRANSMISSION LINE.

Item	Criterion	Weight
1	National Parks	100
2	Official conservation areas excluding national parks	100
3	Private conservation areas and priority sites	100
4	Sites of cultural significance and of cultural events or manifestations or indigenous cultural activities	100
5	Presence of indigenous communities	100
6	Human settlements	100
7	Aquatic bodies	100
8	Distance buffer to conservation sites or sites of interest	
8.1	Buffer from 0 to 91 meters	100
8.2	Buffer from 91 to 183 meters	47
8.3	Buffer from 183 to 274 meters	29
8.4	Buffer from 274 to 366 meters	15
9	Open Field	5
10	Road Network	4

2.2.2 *Technical criteria*

The technical criteria analyzed in this section are associated with the topography of the terrain (elevation and slope), whose input data were acquired through the use of raster images. Additionally, the angular break of the route is another technical criterion, which is intended to mitigate the zigzagging of the transmission line route, as discussed in more detail in section 2.6.

The topographic map was acquired from the U.S. Geological Survey (USGS) database [30], which has a resolution of 1 m. From this source, elevation and slope data were obtained using a digital elevation model and subsequently transformed into a 50×50 m raster resolution. The resulting elevation raster is then used to weight the technical criteria, which are combined with the socio-environmental criteria in the optimization problem described in A.

Technical criteria are established based on terrain topography data, which directly impacts transmission line construction. In this sense, building on sloping terrain translates into less spacing between structures, which translates directly into a higher cost per kilometer, and slopes can make it difficult to access construction material [25]. In this work, the elevation and slope of the terrain were considered as primary technical criteria in solving the transmission line routing problem. For that purpose, two criteria of interest in solving the routing problem were considered:

(i) The elevation angle: It represents the angle of elevation (or angle of depression) between neighboring cells i and j within the routing guide. This angle, denoted as $\alpha_{i,j}$, is a key parameter in solving the routing problem. Therefore, routing under this criterion solves the optimization problem and finds the minimum path by minimizing the angular changes (as a function of elevation) that incur intrinsic penalties. Consequently, when this criterion is purely evaluated, the guide route preferentially avoids elevation changes that may increase the total estimated transmission line weighting, resulting in route sections that are positioned at the same elevation level of the terrain.

(ii) The sloping angle: It is associated with any central cell and its eight neighboring cells, and is represented by $\beta_{i,j}$. In this sense, the central cell β_i calculates the plane using a neighborhood of 3×3 cells (moving window); the slope is calculated as the rate of change of the surface in the horizontal (dz/dx) and vertical (dz/dy) directions [31]. Therefore, routing under this criterion solves the optimization problem and determines the minimum path by minimizing the sum of the slope angles of the cells through which the line route passes, resulting in route sections that are positioned in flat areas. This can be useful for selecting the type of transmission tower that has lower costs and facilitates the transport and assembly of the structures.

Regarding the elevation angle, it is calculated based on the elevation of the horizontal plane (reference cell) to the height of the horizontal plane of the neighboring cell. In Figure 2 it is illustrated the angle of elevation or depression α_{ij} existing in the line segment (i, j) for any pair of neighboring cells within the terrain elevation raster.

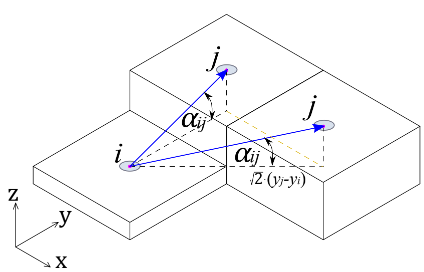

Fig. 2. Elevation angle between pairs of neighboring cells.

Regarding the sloping angle, it was obtained by a transformation of the elevation raster into a sloping raster using GDAL [28]. To understand the angle position, it is similar to the angle of inclination of the surface about the horizontal plane identified in each cell. In that sense, the slope of the terrain is adjusted to a plane formed by the nine local cells to provide a more natural fit to the terrain based on the neighborhood of the cells. Figure 3(a) illustrates the sloping angle β_i of the terrain in each cell and the three-dimensional representation of terrain altitude. Additionally, Figure 3(b) illustrates the link of a pair of neighboring cells (i, j) that is considered as a parameter in this paper.

In relation to the above, Figure 4 shows a three-dimensional representation of terrain altitude to illustrate the behavior of paths on terrain based on optimizing the angles α and

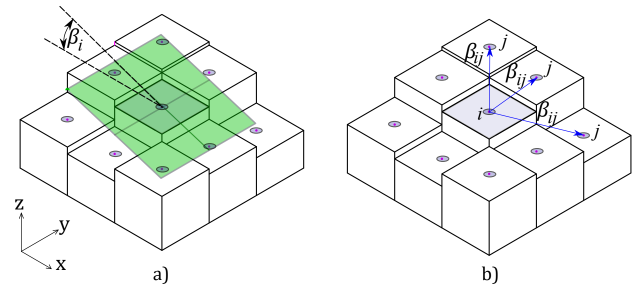

Fig. 3. (a) Slope angle of the central cell with its neighborhood. (b) Average slope of the line section (i, j).

β, respectively. The red path represents the solution when considering only the elevation angle α, positioning the route at a higher level than the blue path. Conversely, the blue path results from considering only the slope angle β, positioning it near the mountain base on flatter terrain. As a result of the optimization process, the route was positioned on flatter terrain due to the weighting of the slope angle, which considers neighboring cells. Consequently, the two parameters evaluated result in two routes that are positioned at different height levels, and with different locations of the cells that form their routes.

To generate a set of alternative routes, it is possible to combine these two parameters to find a middle ground between the benefits offered by these criteria, and some combination of these may be useful for decision-makers. For instance, the path can be positioned in the middle of the ascent height of a mountain, probably bordering it, and this helps to mitigate somewhat the positioning of transmission line towers in the middle of steep slopes along mountain ranges. Steep slopes hinder material access, increasing construction complexity.

In this study, elevation and slope angles are weighted parameters in the optimization problem, as their values depend on terrain conditions. The slope of the terrain is important as an engineering consideration for the location of transmission line towers by soil erodibility (i.e. effect of rainfall defined by its intensity, persistence, and frequency). Slopes in the range of 10° to 17° represent a moderate constraint by increasing construction costs and having a higher likelihood of erosion [11], [25]. Therefore, slopes steeper than 17° should be avoided, if possible, due to high construction and maintenance costs [2], [11]. In this sense, slopes below 10° are the most suitable for the construction and maintenance of an overhead transmission line [25], [32].

Since terrain slope can limit access and impact construction costs, a penalty curve is defined as a function of slope. The penalty is based on a quadratic function, and its objective is to assign a lower penalty to those angles of the section below 10°. Below this angle, it gives more facilities suitable for construction. Conversely, larger angles receive a larger penalty that increases quadratically to provide a constraining feature

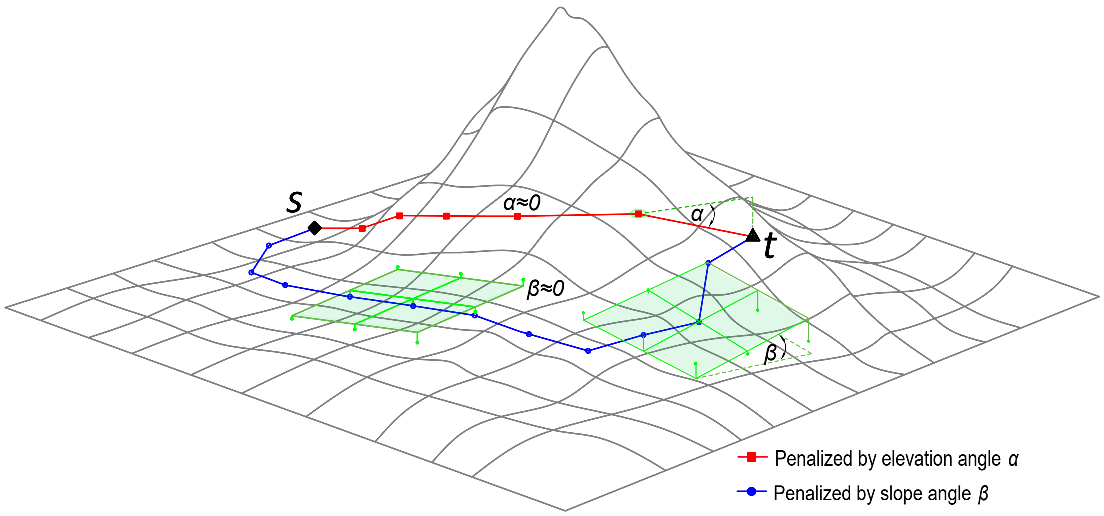

Fig. 4. Behavior of the routes on terrain based on optimizing angles α and β.

within the optimization problem for those line sections.

2.3 *Data structuring*

The GIS raster structure consists of a regular matrix of square cells, each representing a spatial unit. The detail of the geospatial analysis depends on the size of the elementary cell (resolution). In this way, the matrix corresponds to a geographical coverage of the complexity of the terrain (slope of the terrain, land use, and other aspects), and the information contained in each element of the matrix corresponds to the numerical information associated with the corresponding location (land use weighting, average slope surrounding the location, etc.) [15].

To represent the transmission line sections, we use the structure from the raster to create a directed graph. Figure 5(a) shows the structure of the information given by GIS, which is very common in systems based on lines, links, and nodes that are located in the Cartesian plane. Figure 5(b) shows the link created between a cell i with respect to its neighboring cells. Every node of the raster has a name that allows for identifying their position concerning others, which is useful for reading the information before solving the optimization problem. Therefore, solving the optimization problem yields the set of nodes that belong to the route.

2.4 *Finding routes*

To generate alternative routes, it is necessary to solve the optimization problem by varying of some factors that multiply the weighting of socio-environmental criteria and technical criteria, respectively. Regarding technical criteria, there are two components associated with the elevation angle and the sloping angle; within the technical weighting, these components are considered through a convex combination. For example, these

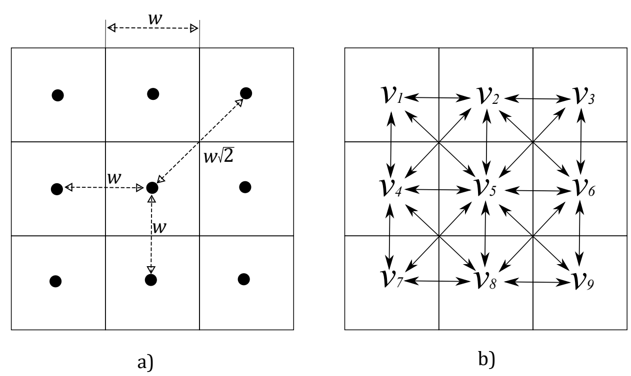

Fig. 5. Structure of the raster data (a) Definition of the distance between cells (b) Links between cell nodes.

factors allow the socio-environmental weighting to be higher than the technical weighting to the extent that areas of high social interest are not crossed by the transmission line, and they allow the route to be positioned according to topography in areas of low socio-environmental impact. Similarly, the convex combination within the technical criterion allows positioning the path between a flat area and a sloped area at a certain altitude.

The mathematical formulation is presented in the Appendix, and it is represented through integer programming. The objective function contains the combination of the socio-environmental and technical criteria described in the section 2.2.1 and section 2.2.2 that are considered to obtain the alternative routes.

As a result of solving the optimization problem by the variation of factors, a set of paths placed on the expansion of land is generated. Each path has associated with a set of unique factors, however, it is possible to recognize some similarities between them over the terrain. In this sense, a clustering process is used to label and recognize the closest path to the centroid in every cluster.

2.5 Clustering

Transmission line routes, when mapped, may overlap or be in close proximity, enabling the formation of clusters. The different geographical positions of transmission line routes can be recognized through artificial intelligence using deep learning methods that facilitate the recognition of a wide range of features. The Convolutional Neural Network (CNN) is one of the most popular methods used in deep learning [33]. Therefore, CNN is widely used as an object classification method, which is an important development for image analysis.

The present work uses Visual Geometry Group (VGG) based CNN. VGG16 [34] is a pre-trained deep learning model that enables clustering using small datasets by comparing feature vectors and invariant data. To identify individual route features, 1:1 aspect ratio binary images of their pixels were used, and each image was stored in *png* format to ensure compatibility with the data loading process. The cells in images describe the transmission line which helps the recognition by VGG16, resulting in the feature vector required for clustering.

Furthermore, the optimal number of clusters was determined using the Elbow Method [35]. The Elbow Method is based on the k-means algorithm that minimizes the sum of the quadratic distances of each route to the centroid of its cluster, which is useful for determining the optimal number of k clusters of routes [35], [36]. The parameter k is obtained by testing a range of values in question, which are plotted allowing to identify the point of curvature (elbow) from which the percentage of the total variance of the data decreases markedly.

Finally, the clusters of transmission line routes are obtained by grouping the features extracted using CNN. By applying the number of k clusters, the sum of the internal variances of the clusters reaches its minimum possible value, allowing each path to be identified and associated with a specific cluster. Each cluster is then identified by a color and a name for easy visualization and access to the data. Figure 6 shows the stages of the clustering process applied in the set of paths.

2.5.1 Refining routes

The routing process is driven by the optimization problem. The raster layer data originates from polygons (as shown in Figure 7(a) or raster datasets at a specific resolution. In that sense, the raster data form a matrix of dimensions n rows and m columns, where each position is part of the node set. Additionally, each node has a connection to its neighboring nodes forming a link structure. Therefore, for the storage of the information associated with the connections between each node with its neighbors, $A_{k,k}$ is created, where k is the total number of nodes within the raster.

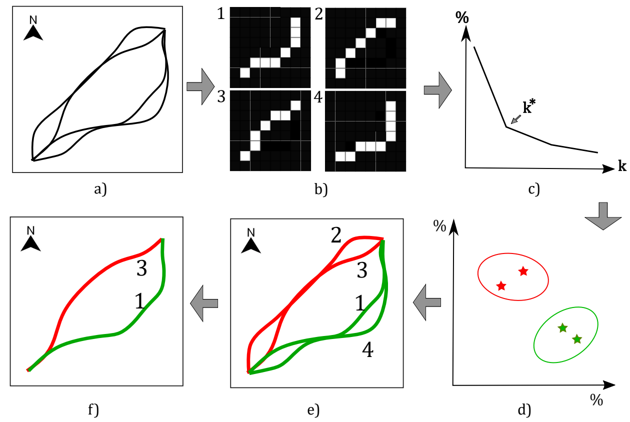

Fig. 6. Clustering process. (a) Set of transmission line routes. (b) Binary images generated for CNN. (c) Application of the elbow method. (d) Clustering with k-means. (e) Resulting clusters. (f) Selecting path close to centroid.

As a result, the required computational memory space tends to grow exponentially when the raster contains higher data resolution density (smaller cell size). However, it is possible to efficiently manage the memory space utilization if the four steps mentioned below are applied:

(i) Obtain from the first guide path by using a raster of lower resolution (larger cell size).
(ii) Generate and select a buffer of cells around the first guide path.
(iii) Change the raster to a higher resolution.
(iv) Select the resized cells within the buffer to generate a new base-link structure, and solve the optimization problem again.

As mentioned above, using a full raster resolution may slow down the computational time and exceed the memory limit depending on the extent of the studio area. For this reason, the transmission line guidance path was obtained by initially using a lower raster resolution to speed up the computational processing, e.g. it is illustrated in Figure 7(b). In this sense, all primary alternative paths were acquired using this same raster resolution.

After the clustering process, the path closest to the centroid in each cluster is chosen. Since the resulting paths had low resolution, the raster cell size was rescaled to enhance data quality and improve resolution. Therefore, the primary path is used as a guide to select a buffer of neighboring cells through which the route passes within the new, higher-resolution raster. This step reduces the loss of information and improves the path details in solving the optimization problem.

Figure 7(c) illustrates the cell selection and the route calculated from the new raster. However, in the routing process, there are sharp variations or zigzags in the positioning of the nodes connecting the transmission line. Therefore, the zigzagging present in the guide path may be composed of closed deflection angles that differ from a realistic guidance path.

2.6 Smoothing routes

The importance of reducing zigzagging lies in the need to facilitate construction by ensuring straight sections, and allows for a reduction in the number of angled transmission towers used to support steep angles ranging from 3° to 45° [37]. Angular towers are structurally built with higher mechanical strength and contain more material. In addition, to withstand the existing bending stresses, larger foundations are required prior to tower placement, which increases overall project costs. Consequently, the cost of this type of tower is higher than that of suspension towers used in straight transmission line sections and may impose limitations on technical and economic decision-making due to elevated construction expenses.

To mitigate these challenges and optimize the use of angular towers, a smoothing process was applied to the routes. This approach ensures a more realistic path while efficiently integrating angular towers within the design. To achieve this, the (Optimal) Rapid Random Trees algorithm was used to create straight sections within a corridor.

2.6.1 Rapidly-Exploring Random Trees

To address the zigzagging observed along the guide path, as shown in Figure 7(d), a smoothing process is applied. This process begins with defining a buffer zone of specific width around the initial route, creating a workspace where new vertices can be freely placed to generate straight-line segments. The buffer ensures flexibility for refining the path while avoiding unnecessary deviations. Figure 7(e) illustrates the buffer area created around the secondary path.

The smoothing process employs the Rapidly-Exploring Random Trees (RRT) algorithm to explore the navigation environment efficiently and generate an initial feasible solution. RRT functions by randomly selecting nodes within the navigation space and connecting each new node to the nearest existing node in the tree, ensuring that the connecting straight-line segment remains collision-free. This iterative process continues until a path is established from the source to the destination. While RRT is known for its efficiency in quickly generating a path, it does not have the capability to guarantee convergence to an optimal solution [38].

To address this limitation, the (Optimal) Rapidly-Exploring Random Trees (RRT*) algorithm is utilized in this study. RRT* enhances the original RRT by incorporating a mechanism that ensures convergence to an optimal path as iterations progress [39]. This feature makes RRT* particularly suitable for applications requiring both efficiency and optimality. Figure 7(f) demonstrates the execution of the RRT* algorithm within the buffer zone, where nodes (red dots) are incrementally added to the tree structure (green lines) until the target is reached. The resulting path, depicted in Figure 7(g), consists of straight-line segments and represents a smoothed version of the initial route. By applying this process to the representative routes of each cluster, the methodology achieves solutions that balance computational efficiency with practical feasibility, enhancing their applicability in real-world transmission line planning.

2.6.2 Minimum-average and minimum-maximum regret criteria

Regarding the objective function to generate routes, the variation of one of the parameters leads to a new composite optimization problem with its corresponding objective function . Therefore, solving the optimization problem results in an optimal route that fits the parameters entered. Because of this, when a route is evaluated from the perspective of a different objective function from its corresponding one, its relative weighting is increases due to the suboptimal evaluation.

In that sense, it is possible to make a comparison of a route from the point of view of different objective functions. To achieve this, an regret matrix associates the objective functions of various routes with the selection of a specific route. By using minimum-average and minimum-maximum regret criteria, it could be useful to select a route that is the most attractive or representative among the others from the criterion of the minimum relative value.

The minimum-average and minimum-maximum regret criteria consist of forming a vector containing the average or maximum of each row (a path evaluated reciprocally with each objective function) of the regret matrix, respectively. The vector containing the average or maximum of each row is used to find the position. The position of the minimum or maximum value within the vector represents a particular route, which in turn has the lowest average weighting (or lowest total value among its maximum) against the other alternatives.

3 Case study

3.1 Case description

This paper presents a case study focused on the area surrounding Copiapó, located in the Atacama region of Chile. The study involves the installation of a transmission line connecting the origin substation, S/E_1 (466503E, 7027870N), to the destination substation, S/E_2 (493079E, 6988908N). The Universal Transverse Mercator (UTM) zone 19S reference system was used to define the geographical information layers. The distance between the two substations is approximately 47 km.

The study area is defined by a rectangular region measuring 30 x 43 km, encompassing the planned route of the transmission line. This region features critical socio-environmental

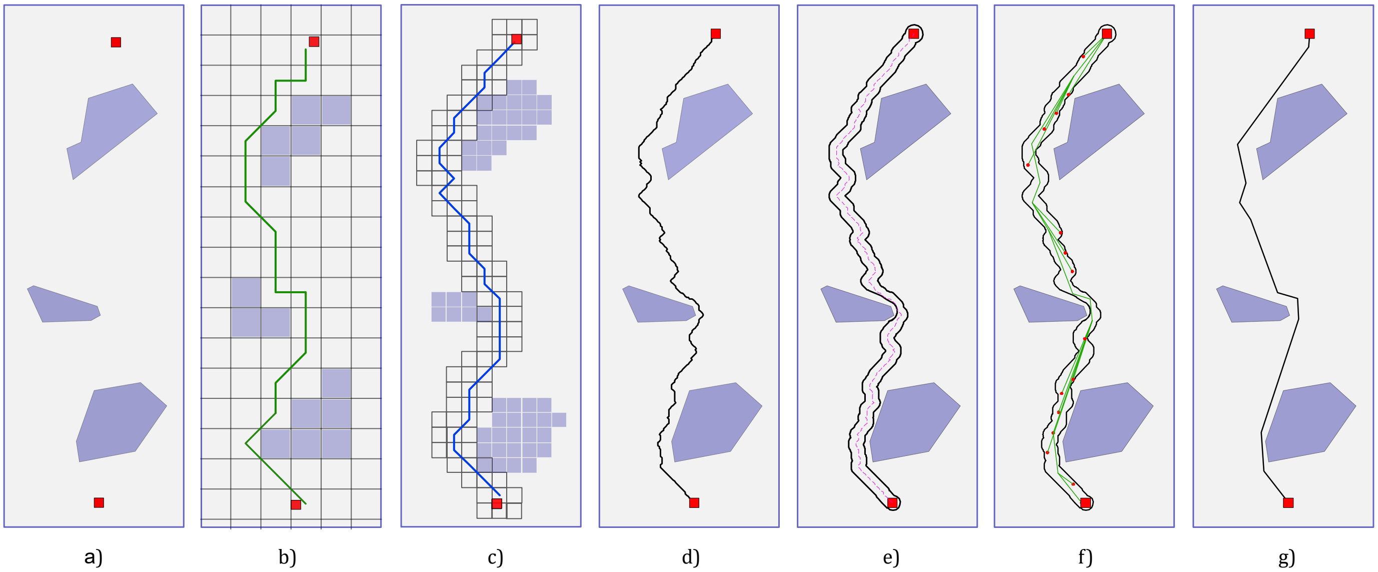

Fig. 7. Raster resizing for routing (a). Initial general criteria layer. (b) Lower resolution raster layer, to acquire the guide path. (c) Higher resolution layer, associated with the rasterization of the neighboring cells of the guide path (d) Initial path for smoothing (e). Route buffer. (f) Execution of the RRT* algorithm. (g) Smoothed path result.

considerations, including indigenous communities, roadways, national parks, salt flats, and Ramsar wetlands. These elements present significant challenges and opportunities for the routing process. Figure 8 illustrates the prohibitive zones within the study area, highlighting the factors that shape route selection.

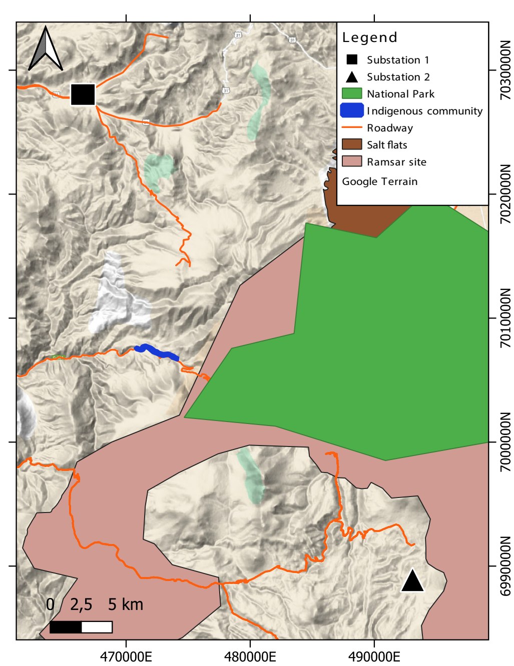

Fig. 8. Case study area.

3.2 Input data

To build a weighted surface to represent the complexity of crossing the transmission line over the area, it was used maps associated with national parks, urbanized areas, and aquatic bodies among other categories were obtained through the information available on platforms such as the Chilean Geospatial Data Infrastructure (IDE) [40] and the OSM [41]. Additionally, [25] presented a list of institutions that have Chilean public databases that can be a source of information to generate new raster layers. In the present work, QGIS was used in the management of the initial raster layers, and the size of cells used for raster maps was 50x50 m.

Furthermore, other aspects like handling of materials for the construction of the transmission line through roads were considered in the routing. In that sense, the layout of roads in the study area can give a degree of preference in the transmission line routing process due to the benefit associated with accessibility through these existing roads.

4 Results and Discussion

Figure 9 presents the 91 routes identified through the proposed methodology. As observed, many of these routes exhibit geospatial similarity. Therefore, a clustering process was applied to group similar routes, resulting in a representative route for each cluster. These routes were initially generated using a raster grid with a resolution of 200×200 m. Subsequently, a refinement process was applied to the five representative routes using a higher resolution of 50×50 m.

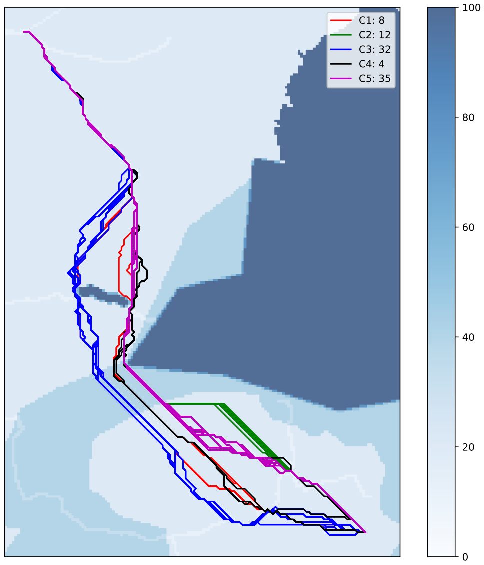

Fig. 9. Classification of the 91 identified routes into five clusters using the proposed methodology.

Figure 10 illustrates the stages involved in trajectory smoothing. . In Figure 10(a), the initial routes are displayed, each representing a cluster. These routes exhibited significant zigzagging. To address this, a 250 m buffer was created around the guidance lines, as shown in Figure 10(b), providing the necessary space for trajectory smoothing through straight segments. The vertex points were optimized using the RRT* algorithm, resulting in the smoothed paths shown in Figure 10(c). These final paths consist of rectilinear sections, effectively reducing the zigzagging of the initial routes.

Figure 11 highlights five final routes overlaid on different raster maps, showcasing socio-environmental and technical criteria such as terrain elevation and slope gradient. These maps were used as inputs to the optimization model, ensuring that the routing process accounted for the diverse factors influencing route selection. The geographical positioning of the routes demonstrates a variety of solutions that cater to the decision-making needs of stakeholders by balancing technical and socio-environmental priorities.

The proposed methodology facilitates the selection of routes based on the terrain characteristics they cross. Sections A, B, and C (Figure 11) exemplify how decision-makers can use this menu of route alternatives to prioritize options that align with their objectives. The following highlights the characteristics of the routes in each section:

- Section A: All routes follow the roadway, where the slope does not exceed 10°. This slope threshold ensures that materials can be easily transported to construction sites. Here, social preference dominates, as the topography poses minimal challenges. It is important to note that, in Table I, roads are assigned the lowest weight, indicating that from a mathematical optimization perspective, they are the most preferable option for transmission line routing.
- Section B: Routes p_2, p_4, and p_5 are positioned to the right of an indigenous community, avoiding significant socio-environmental impacts. Routes p_2 and p_5 exhibit less zigzagging, indicating reduced topographical challenges compared to p_1 and p_3, which prioritize minimizing altitude changes and slopes on the left side of the community.
- Section C: Routes p_1 and p_3 prioritize flatter areas to minimize slopes, with p_3 using an extended roadway for added social preference. Route p_4 combines minimization of slopes and altitude changes, skirting the base of the mountains. Conversely, p_5 crosses higher elevations, demonstrating minimal influence of topographical considerations in this segment.

Figure 12 shows the height profiles of the original and smoothed routes for each cluster. The smoothing process resulted in shorter final routes, with an average length of approximately 60 km, highlighting the effectiveness of the optimization in reducing unnecessary zigzagging.

Table II presents the regret matrix, which summarizes the performance of each route across various objective functions using the min-average (min-avg) and min-maximum (min-max) regret criteria. The value assigned to each route depends on the configuration of parameters input into the objective function before solving the optimization problem. Notably, adjustments to these parameters can lead to variations in the selected route.

TABLE II
REGRET MATRIX FOR CASE STUDY, AND APPLICATION OF MINIMUM-AVERAGE AND MINIMUM-MAXIMUM REGRET SELECTION CRITERIA.

$\mathcal{P}$	Objective Function					Minimum	
	OF_1	OF_2	OF_3	OF_4	OF_5	Average	Maximum
p_1	**1.00**	1.08	1.00	1.06	1.09	**1.05**	**1.09**
p_2	1.06	**1.00**	1.09	1.19	1.00	1.07	1.19
p_3	1.01	1.11	**1.00**	1.09	1.12	1.06	1.12
p_4	1.13	1.10	1.25	**1.00**	1.09	1.11	1.25
p_5	1.09	1.00	1.12	1.24	**1.00**	1.09	1.24

In this matrix, each row represents a specific route evaluated under different objective functions, while each column reflects the total penalty associated with a particular objective function across all routes. To normalize the data, each value $M_{i,j}$ in the regret matrix is computed as $M_{i,j} = C_{i,j}/C_{j,j}$, where $C_{i,j}$ is the cost of route i under objective function j, and $C_{j,j}$ is the cost of the optimal route for that objective function (i.e., the value on the main diagonal)

This formulation allows for the assessment of how the cost of an objective function changes when applied to different routes. For instance, if we consider the first column (OF_1),

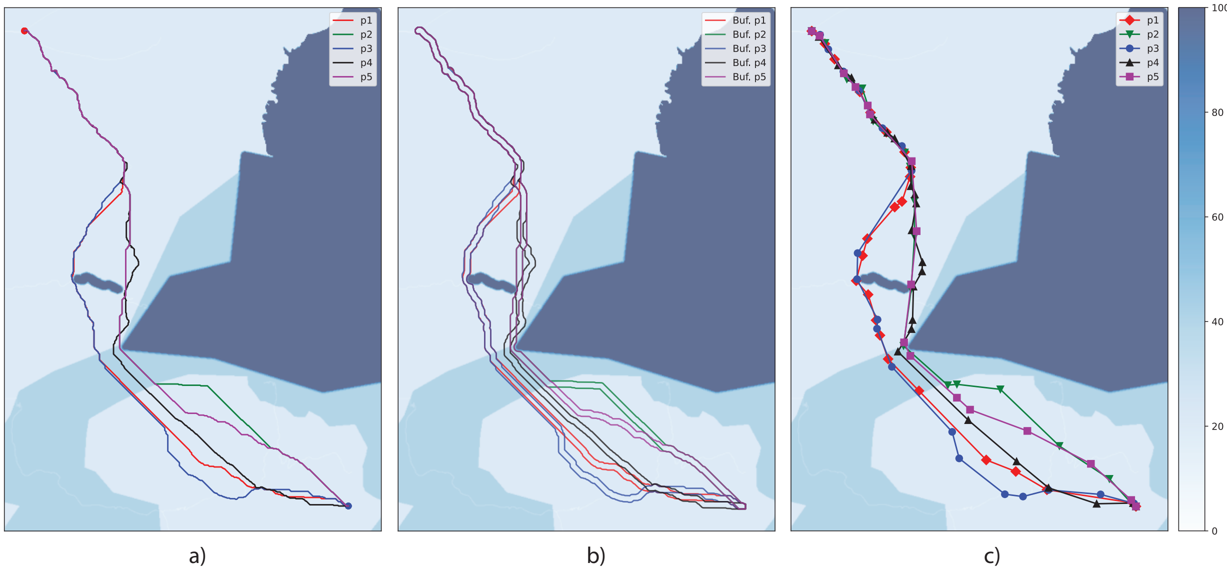

Fig. 10. Route stages of case study for each cluster. (a) Initial routes. (b) Buffered routes. (c) Smoothed routes.

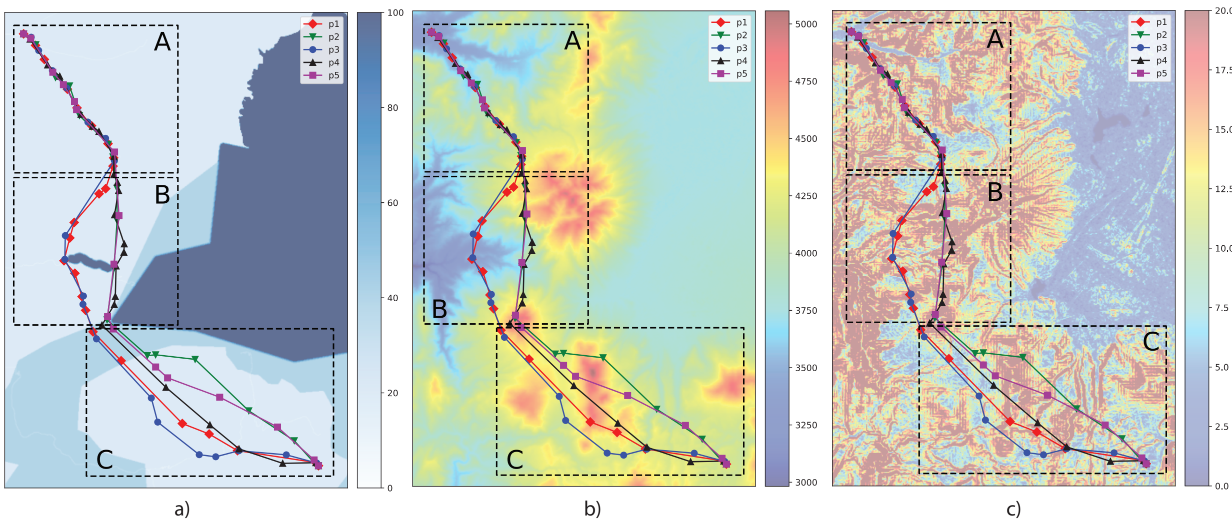

Fig. 11. Case study final routes on different maps. (a) Raster map of socio-environmental criteria. (b) Raster map of terrain elevation, expressed in m.a.s.l. (c) Raster map of terrain slope, expressed in degrees.

the diagonal element is equal to 1, indicating the optimal route for OF_1. If another cell in the same column, such as path p_2, has a value of 1.06, this implies that the cost of OF_1 increases by 6% when evaluated on path p_2 instead of the optimal path

Applying the min-avg and min-max regret criteria to this matrix allows for the selection of routes that perform consistently well across multiple objective functions. In many cases, both criteria tend to select the same route, indicating its relative advantages over other alternatives. However, depending on the spatial distribution and the weightings of the criteria influencing the transmission line's path, the selection may be narrowed down to two competing routes. In this case, route p_1 demonstrated the most balanced performance, making it a suitable choice for stakeholders considering different trade-offs in the decision-making process.

5 Conclusions

This work presents a novel methodology for transmission line routing that systematically generates optimal routes by integrating technical and non-technical criteria, including technical, environmental, social, and economic considerations. The methodology employs raster images to represent weighted maps of prohibitive zones, which are then converted into a spatially coherent structured network of nodes, facilitating efficient optimization using Dijkstra's algorithm. The resultant set of route alternatives demonstrates diversity, with each route optimized according to a unique combination of criteria. To

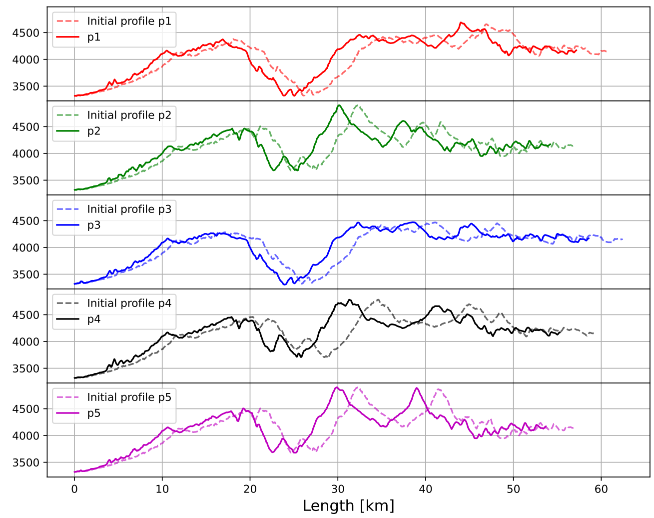

Fig. 12. Altitude profiles of the case study.

enhance the usability and realism of the results, similar routes were clustered based on spatial proximity and refined through a smoothing process to minimize zigzagging.

The results of the case study highlight the efficacy of this approach in navigating prohibitive land-use areas while strategically diversifying transmission line placement. By assigning significance to socio-environmental and technical criteria, the methodology produces route alternatives that reflect attributes of interest to decision-makers, promoting informed and balanced decision-making.

A key feature of this work for planners and decision-makers is the introduction of a regret matrix to compare route alternatives. By applying minimum-average and minimum-maximum regret criteria, the most beneficial route can be identified based on a combination of attributes. However, it is essential to recognize that the selection of the "best" route is context-dependent. The regret matrix should therefore be viewed as a supportive tool for assessing trade-offs and accommodating diverse stakeholder perspectives, rather than a definitive decision-making mechanism.

Future research directions include incorporating angular optimization to reduce or eliminate deflection angles and sharp curves in the final route layout [3]. Additionally, integrating the Optimum Spotting algorithm [42] could enhance the methodology by determining the ideal placement of towers along the guide.

This methodology represents a significant step toward sustainable, socially acceptable, and technically sound transmission line planning, offering a comprehensive toolkit for addressing the complexities of infrastructure development in diverse socio-environmental contexts.

Declaration of Competing 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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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used GPT-4 to enhance the clarity of select portions of the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Appendix

A Notation

In this section, we show the formulation of the mathematical problem that is used to solve this approach.

1.1.1 Sets

$\mathcal{E}$	Set of transmission line sections (i, j)
$\mathcal{L}$	Set of evaluation criteria layers k
$\mathcal{N}$	Set of nodes i
$\mathcal{P}$	Set of routes p of transmission lines

1.1.2 Variables

x_{ij}	Binary decision variable, where: • $X_{ij} = 1$ if line section (i, j) is built • $X_{ij} = 0$ otherwise

1.1.3 Parameters

A_{ij}	Average weight of the socio-environmental criteria between nodes i and j
B_i^{AMB}	Total value of the node i for the socio-environmental criterion
$B_{i,k}$	Weighted value of the node i of the layer k
d_{ij}	Distance of the line section (i, j) [m]
$f(\alpha_{ij}\ )$	Quadratic function for line-span elevation angle penalty between nodes i and j
$f(\beta_{ij}\ )$	Quadratic function for penalization of the slope angle between nodes i and j
H^{ELV}	Quadratic term for the elevation angle penalty
H^{SLP}	Quadratic term for slope angle penalty

I_k^{AMB}	Socio-environmental impact of the k layer
J^{ELV}	Linear term for the elevation angle penalty
J^{SLP}	Linear term for the slope angle penalty
L^{ELV}	Constant term for elevation angle penalty
L^{SLP}	Constant term for the slope angle penalty
Q^{AMB}	Socio-environmental criteria multiplier
Q^{TEC}	Technical criteria multiplier
R_{ij}^{ELV}	Weighting of the angle of elevation or depression between nodes i and j
T_{ij}^{SLP}	Weighting of the slope angle between nodes i and j
W_{ij}^{AMB}	Weighting associated with socio-environmental criterion between nodes i and j
W_{ij}^{TEC}	Weighting associated with technical criterion between nodes i and j
w	Raster cell size [m]
α_{ij}	Angle of elevation or depression from node i to node j [°]
β_{ij}	Angle of slope between nodes i and j [°]
λ_{ij}	Parameter for linear combination between technical criteria R and T

B Formulation

The formulation for finding routes based on nodes and links significant is represented through integer programming and implemented in Julia Language [43]. To solve the optimization problem, Dijkstra's method [44] was used because of computational processing time benefits.

1.2.1 Objective function

The objective function seeks to minimize the overall value of weighting of land use of a transmission line, including two topographic considerations in the decision-making. In this sense, the model of the objective function corresponds to the one developed to find the shortest path. Then, the formulation is given by a directed graph $G = (\mathcal{N}, \mathcal{E})$ where $\mathcal{N}$ is the set of nodes and $\mathcal{E}$ is the set of transmission line spans, it is desired to find a path $p = (v_s, \dots, v_t)$ where $v_i \in \mathcal{N}$. Each link $(v_i, v_j) \in \mathcal{E}$ has a weighting associated with the socio-environmental W_{ij}^{AMB} and technical criteria W_{ij}^{TEC}. Consequently, a path $p \in \mathcal{P}$ will have a combined weight corresponding to the sum of the weightings of the line sections traveled.

$$\min_{x_{ij}} \sum_{(i,j) \in \mathcal{E}} x_{ij} \cdot (Q^{AMB} \cdot W_{ij}^{AMB} + Q^{TEC} \cdot W_{ij}^{TEC}) \quad (1)$$

Where, the decision variable x_{ij} indicates whether a link (i, j) is part of the shortest path. The variable x_{ij} is multiplied by the estimated weighting on those links (i, j) which is distributed between the parameters W_{ij}^{AMB} and W_{ij}^{TEC}. Each member of the weighting of the criteria of interest is then multiplied by its corresponding parameter Q^{AMB} and Q^{TEC} to give a higher degree of relevance to one of the criteria. For example, these factors allow the socio-environmental weighting to be higher than the technical weighting to the extent that areas of high social interest are not crossed by the transmission line, and allow the route to be positioned according to topography in areas of low socio-environmental impact.

In the case study (Section 3), the parameters Q^{AMB} and Q^{TEC} were adjusted within the ranges Q^{AMB}=[0.3, 30] and Q^{TEC}=[0.01, 1], respectively, to generate a sufficient number of solutions (91 routes) that capture the diversity of alternatives observed in practice. After each adjustment, the results were analyzed to determine whether further modifications were necessary, ensuring that the model effectively explored the solution space. These solutions were subsequently refined through a clustering technique to obtain a representative set of routes.

1.2.2 Model constrains

The objective decision variable is to select the set of edges (transmission line sections) that form the minimum total weighting to go from the originating node s to the receiving node t corresponding to the subset of links that represents the least cost route for the transmission line. The constraint (2) requires that only one edge is active going from s to an adjacent edge, (3) requires that only one edge reaches the sink, (4) requires that at most one edge is active between nodes i and j. In addition, (5) provides non-negativity for the decision variables. In this sense, the total weighting is calculated by applying Dijkstra's shortest path algorithm [44]. By applying the algorithm, the result obtained corresponds to the subset of links that belongs to $\mathcal{E}$, and it represents the least complex path for the transmission line.

$$\sum_j x_{sj} - \sum_j x_{js} = 1 \quad (2)$$

$$\sum_j x_{tj} - \sum_j x_{jt} = -1 \quad (3)$$

$$\sum_j x_{ij} - \sum_j x_{ji} = 0, \quad \forall\ i \in \mathcal{N} \ / \ \{s,t\} = 0 \quad (4)$$

$$x_{ij} \geq 0;\ \forall\ (j,i) \in \mathcal{E} \quad (5)$$

1.2.3 Socio-environmental parameters

The social-environmental parameter defines the weighting of the line section between the node i and j, that is multiplied by squared two depending on the direction of the line section.

$$W_{ij}^{AMB} = \begin{cases} A_{ij}, \textit{if vertical or horizontal} \\ \sqrt{2} \cdot A_{ij}, \textit{if diagonal} \end{cases}, \forall\ (i,j) \in \mathcal{E} \quad (6)$$

The parameter B_i^{AMB} contains the value of the socio-environmental criterion at node i. The average of the weighted value between the node i and j is obtained through the parameter A_{ij}.

$$A_{ij} = \frac{B_i^{AMB} + B_j^{AMB}}{2}, \forall\ (i,j)\ \in\ \mathcal{E}, i \in\ \mathcal{N}, j \in\ \mathcal{N} \quad (7)$$

Concerning the parameter B_i^{AMB}, it is calculated by the algebraic sum of the overlapping values at a node i, then, it is multiplied by an impact factor I_k^{AMB} that gives a relevance between the different layers of the set of layers associated to the socio-environmental criteria.

$$B_i^{AMB} = \sum_k B_{ik} \cdot I_k^{AMB}, \forall\ k \in\ \mathcal{L}, \forall\ i \in\ \mathcal{N} \quad (8)$$

1.2.4 Technical parameters

To calculate the elevation angle α_{ij}, illustrated in Figure 2, the vector component associated with the plane xy is employed, and it is the cell size of the raster. The component xy is multiplied by $\sqrt{2}$ for diagonal transitions to neighboring cells, or it is multiplied by 1 for vertical and horizontal transitions inside the plane xy. Cells are represented by cartesian coordinates (x_i, y_i, z_i). The elevation variation (dz), defined in z axis, provides the complementary component used for the angle calculation.

$$\alpha_{ij} = \begin{cases} \left|\tan^{-1}\left(\frac{z_j - z_i}{y_j - y_i}\right)\right|, \textit{if vertical or horizontal} \\ \left|\tan^{-1}\left(\frac{z_j - z_i}{\sqrt{2}(y_j - y_i)}\right)\right|, \textit{if diagonal} \end{cases}, \quad \forall\ (i,j)\ \in\ \mathcal{E}, i\ \in \mathcal{N},\ j\ \in \mathcal{N} \quad (9)$$

On the other hand, the sloping angle β_{ij} illustrated in Figure 3(b) is calculated using the average between sloping angles stored in cells i and j.

$$\beta_{ij} = \frac{\beta_i + \beta_j}{2},\ \forall (i,j) \in \mathcal{E}, i\ \in \mathcal{N},\ j\ \in \mathcal{N} \quad (10)$$

The total weighting associated with the technical criteria W_{ij}^{TEC} is distributed between two components: R_{ij}^{ELV} and T_{ij}^{SLP}, which are associated with the angle of elevation and the angle of slope between the nodes of a route section, respectively. Additionally, the parameter λ defines the linear combination between these two factors.

$$W_{ij}^{TEC} = R_{ij}^{ELV} \cdot \lambda + (1-\lambda) \cdot T_{ij}^{SLP}, \quad \forall (i,j) \in \mathcal{E}, \quad \lambda \in [0,1] \quad (11)$$

In relation to the angle of elevation or depression, R_{ij}^{ELV} is obtained by evaluating the quadratic function (14). This penalty gives less opposition to lower elevation angles in comparison to higher ones. Similarly, T_{ij}^{SLP} for sloping angle is obtained by evaluating the quadratic function (15), where it gives less opposition to the smaller slope angles in comparison to the larger ones.

$$R_{ij}^{ELV} = \begin{cases} f(\alpha_{ij}) \\ \sqrt{2} \cdot f(\alpha_{ij}) \end{cases}, \forall\ (i,j)\ \in\ \mathcal{E} \quad (12)$$

$$T_{ij}^{SLP} = \begin{cases} f(\beta_{ij}) \\ \sqrt{2} \cdot f(\beta_{ij}) \end{cases}, \forall\ (i,j)\ \in\ \mathcal{E} \quad (13)$$

The quadratic functions penalize the angle α y β existing between a node i and j to represent the technical criteria. In addition, the coefficients H, J y L within the quadratic functions, both for elevation and sloping angle, are used to adjust the penalty curve shape as necessary. However, it can also be modified into a biquadratic function to improve the penalty curve characteristic. Particularly, in the case study, a biquadratic function was used, where the following values were assumed: $H = 1\text{x}10^{-4}$, $J = 1\text{x}10^{-4}$, and $L = 1$ for both elevation and slope terms. These values were chosen to generate a curve that assigns a lower penalty to section angles below 10 degrees.

$$f(\alpha_{ij})\ = H^{ELV} \cdot \alpha_{ij}^2 + J^{ELV} \cdot \alpha_{ij} + L^{ELV}, \forall\ (i,j)\ \in\ \mathcal{E} \quad (14)$$

$$f(\beta_{ij})\ = H^{SLP} \cdot \beta_{ij}^2 + J^{SLP} \cdot \beta_{ij} + L^{SLP}, \forall\ (i,j)\ \in\ \mathcal{E} \quad (15)$$

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