Integrating geographic intelligence for sustainable powerline planning

Integrando inteligência geográfica para o planejamento sustentável de linhas de transmissão de energia

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ABSTRACT

This research explores the potential of geographic intelligence in modelling optimal corridors for assessing alternative locations for power transmission lines at different stages of the study. The difficulties verified in the environmental licensing of new projects, the expansion of the national transmission system, and the lack of work to research techniques for formulating locational alternatives are motivating questions for this research. The investigation employs a multicriteria decision-making approach integrated with a geographic information framework to compute and map the feasibility corridors based on environmental constraints and stakeholder inputs. Findings reveal that the current decision-making process for implementing new power transmission lines involves disparate public and private entities operating non-integratively in a multi-level analysis and decision-making process. Through a case study utilising multicriteria analysis and expert consultations, the research demonstrates the applicability of spatial modelling in the locational planning of transmission projects. It highlights the model's capacity to address the complexity inherent in such studies, aggregate analyses and decisions from various stakeholders, and enhance transparency in the decision-making process from energy planning to operational phases.

Keywords: AHP. Powerline planning. GIS. Conceptual model. Participatory model. Decision-making.

RESUMO

A pesquisa investiga o potencial da inteligência geográfica para modelagem de corredores preferenciais para a qualificação da etapa de estudos de alternativas locacionais de linhas de transmissão de energia. As dificuldades verificadas no licenciamento ambiental de novos projetos, a ampliação do sistema de transmissão nacional e a falta de trabalhos direcionados para a pesquisa de técnicas de formulação de alternativas locacionais são questões motivadoras desta pesquisa. O trabalho analisou o emprego de um sistema de decisão implementado em um sistema de informações geográficas baseado em ponderações de atores envolvidos. Constatou-se que o fluxo decisório atualmente instituído para a implantação de novas linhas de transmissão, desde as etapas de planejamento energético até a efetiva operação do empreendimento, envolve diferentes entidades públicas e privadas que atuam de forma não integrada em um processo multinível de análises e decisões. O estudo de caso apresentado envolve técnica de análise multicriterial e a consulta a especialistas. Demonstrou-se a aplicabilidade da modelagem espacial ao planejamento locacional de projetos de transmissão, a sua aptidão para considerar a complexificação presente em estudos desse porte, o seu potencial de agregação de análises e decisões dos diferentes atores que integram o processo decisório e sua capacidade de compreensão e transparência.

Palavras-chave: *AHP. Planejamento de linha de transmissão. Geoprocessamento, modelo conceitual e modelo participativo. Tomada de decisão.*

1 INTRODUCTION

Globalisation Sustainability is a pivotal policy in the contemporary energy sector, albeit posing a formidable challenge for critical infrastructure endeavours like Transmission Power Lines (TPL). The surge in investments in renewable generation facilities worldwide responds to the escalating demand for electrical energy. These renewable power plants, aligned with the 2023 Agenda of the United Nations and specifically contributing to SDG 7 (IEA, 2019), are predominantly located far from consumer centres. However, expanding the power line transmission network is a consequential outcome of these new power plant initiatives. A recent report from Brazil's Ministry of Mining and Energy underscores the imperative need for over 33,000 km of new TPL across the nation by 2031 (MME; EPE, 2022), with the primary driver being the accommodation of new solar and wind power plants, in addition to conventional hydroelectric facilities. Nonetheless, a meticulous analysis necessitates closer scrutiny of such an extensive infrastructural expansion's ramifications and potential environmental consequences.

The strategic planning process for expanding power lines entails considerations encompassing government regulation, socio-environmental impacts, and technological dimensions. The application of Multicriteria Decision Making (MCDM) methods in energy planning has gained widespread acceptance, driven by the intricate nature of the decision-making process (Biasotto *et al.*, 2022; Greening; Bernow, 2004; Kumar *et al.*, 2017; Pohekar; Ramachandran, 2004; WANG *et al.*, 2009). Integrating social and environmental factors, public engagement, and the dynamics of diverse stakeholders in decision-making processes is critical in shaping this complex landscape. Simultaneously, the ongoing global discourse on climate change and sustainable development accentuates the imperative to formulate sustainable design approaches for energy initiatives. Nevertheless, the effective integration of these considerations into energy planning and development practices warrants comprehensive investigation, particularly regarding the practical implementation and enforcement of such measures.

In the context of power lines, the conventional evaluation of alternatives aims to facilitate the identification of the optimal "route or path across a landscape or along existing facilities or rights-of-way in such a manner that criteria such as cost, safety, environmental impact, and aesthetics are all considered simultaneously" (Church; Loban; Lombard, 1992). This approach is the foundation for feasibility studies and, in many cases, has become a mandatory requirement for environmental regulatory agencies.

In the 1990s, authors such as Jankowski (1995) emphasised that addressing challenges associated with establishing a new right-of-way would be more effective through an integrated approach incorporating Geographic Information System (GIS) and Multicriteria Decision Making (MCDM) methods. Nearly two decades later, GIS gained popularity and widespread adoption among professionals in transportation, utilities, and power management fields (Salim *et al.*, 2023). This increased knowledge and evolving demands enabled developers to create geographically intelligent models to address new challenges, including those aligned with Sustainable Development Goals (SDGs). Given that the planning processes for critical infrastructure projects now encompass environmental, socioeconomic, and cultural perspectives in addition to the conventional engineering standpoint, achieving an effective balance of data, roles, and stakeholders has emerged as a fundamental challenge for the intricate decision-making process (Stich *et al.*, 2011). In pursuing comprehensive geospatial solutions, Araújo, Ajuz, and Ramos (2021) proposed an approach incorporating spatial modelling during the scoping phase of the environmental impact assessment. Their study yielded promising preliminary results within the framework of the Brazilian environmental permitting process for transmission lines.

These challenges prompted research from various perspectives, focusing on logical modelling concerning data and algorithms and physical modelling related to software implementation (Costa, 2023). Despite the ongoing advancements within the GIS realm, it is evident that conceptual modelling, crucial for effectively capturing the problem and conceptualising the solution, remains a significant challenge in the energy sector. This concern has led to questions such as: How can we identify options that encompass all stakeholders' input in the decision-making process? Therefore, we hypothesise that a logical approach rooted in a comprehensive conceptual model enables the solution to consider the synergy among different actors participating in the process, facilitating more effective deliberation, evaluation, and prioritisation of Transmission Line Project (TLP) alternatives.

One potential solution, forming the fundamental premise of this research, involves proactively addressing environmental concerns at the outset of decision-making processes related to the planning and executing the expansion of transmission networks. Cardoso Jr. and Hoffmann (2019), in their analysis of the reliability of the Brazilian electricity sector, advocate for, among other measures, the early consideration of environmental issues at the planning stage, incorporating environmental impact assessments into the decision-making process.

Within this context, the present study aims to introduce a spatial modelling framework designed to generate alternatives for power lines. This framework considers environmental, social, and economic criteria, aiming to facilitate the inclusive participation of key stakeholders. The conceptual foundation of this study is rooted in the methodological strategy of corridor planning proposed by Nóbrega *et al.* (2009), employing the Analytic Hierarchy Process (AHP). However, a rigorous examination of this approach is essential, necessitating a critical evaluation of its practical applicability in real-world scenarios and its potential limitations in addressing the intricate challenges inherent in infrastructure planning.

The Brazilian decision-making process was selected as a case study, and the model has been crafted to facilitate its adaptability to diverse decision-making scenarios, spanning various decision levels, stakeholders, and variables. The country presents distinctive characteristics that underscore the challenge of achieving a sustainable expansion of its transmission system, including:

- The escalating growth of renewable energy generation systems and the imperative to connect this surplus to consumer centres (Silva; Marchi Neto; Seifert, 2016; Manso *et al.*, 2012; RUDNICK *et al.*, 2012);
- The intricate relationship between land-use diversity and socio-environmental impacts associated with the implementation and operation of transmission lines;
- Delays in the execution of new projects, as indicated by sector studies (Aneel, 2019);

- The anticipation of an expansion in the current transmission network from 175,273 km to 208,907 km by 2031, entailing an investment of nearly R$ 126.4 billion (MME, 2022).

2 CASE STUDY

2.1 THE BRAZILIAN REGULATORY FRAMEWORK

In the current regulatory framework of the Brazilian energy sector, the implementation and operation of new Transmission Power Lines (TPLs) occur through public concession to private or public entities. Locational studies for the right-of-way are initiated during the project planning phase, with environmental licensing undertaken subsequently. Public institutions conduct the initial engineering planning studies to guide the bidding process, while environmental licensing commences after the bidding process with the first results provided by the concessionaires (Cardoso Júnior *et al.*, 2014). The National Electric Energy Agency (Aneel) oversees the TPL auction, which involves public bids for the concession of transmission lines. The concession establishes a contractual agreement between the awarded company and Aneel, focused on the construction and operation of the project for a specified period, considering an annual revenue stipulated in the contract.

In the planning stage, corridor alternatives are assessed in the first report (R1). The second report encompasses an internal process detailing the project's technical specifications. Subsequently, the third report (R3) provides a socio-environmental characterisation of the selected corridor and proposes a track guideline (EPE, 2005). Historically, R1 and R3 have faced criticism due to issues related to visibility and interdisciplinary interests, including external control. These documents furnish the auction with information regarding the potential location of the project.

Brazil's administrative procedure mandates that activities utilising environmental resources or contributing to environmental degradation undergo an authorisation process by a governmental environmental entity (Sanchéz, 2006). The development and analysis of locational alternative proposals for a new project occur in the initial stage when project proponents request the preliminary license. Federal or state environmental agencies can administer the licensing process as Brazilian law stipulates. The Environmental Impact Assessment (EIA) commences after the TPL auction. Typically, environmental licensing follows a three-phase model, issuing three licenses (Conama, 1997), as delineated in Table 1.

Table 1 | Phases of environmental licensing in Brazil

Environmental Licensing phase	*Description*
Preliminary License	Issued during the initial phase of the project or activity, the permit approves its location and design, verifies its environmental feasibility, and establishes the fundamental requirements and conditions to be fulfilled in the subsequent stages of implementation.
Installation License	Permits the installation of the project or activity under the specifications outlined in the approved plans, programs, and projects, encompassing environmental control measures and other stipulated conditions.
Operation License	The authorisation for the operation of the activity or project is subject to the verification of the actual fulfilment of the prerequisites stipulated in the preceding licenses and compliance with the specified environmental control measures and operational conditions.

Within the existing decision-making framework, locational studies are formulated during the planning stage and deliberated during the environmental licensing phase. This process engages diverse actors with distinct institutional roles, resulting in varying perspectives and interests in the project. The decision flow, spanning from design to operation, encourages the participation of a multitude of public and private stakeholders who scrutinise technical studies and contribute to decision-making, as illustrated in Figure 1. The roles of the mentioned stakeholders in the decision-making process are delineated in Table 2.

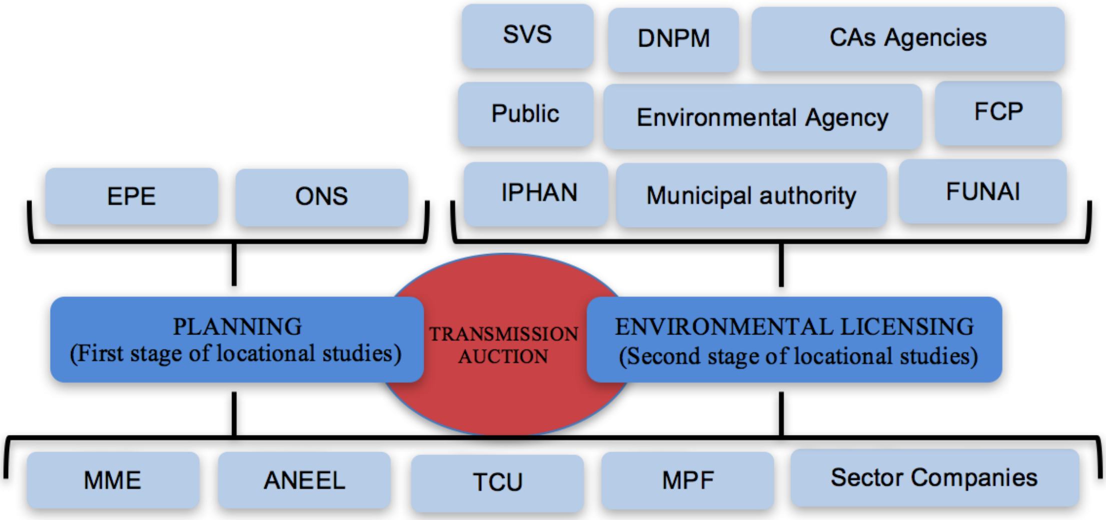

Figure 1 | Framework of stakeholders engaged in the planning and environmental permitting of Power Transmission Lines within the Brazilian regulatory framework.

Source: Adapted from Cardoso Júnior et al. (2014), Lima and Magrini (2010) and Silva (2009)

Table 2 | Entities engaged in the planning and licensing of transmission line projects within the Brazilian regulatory framework

Actors	*Attributions*
Ministry of Mines and Energy (MME)	A public entity responsible for the overall planning of energy generation, mining, and production of oil, gas, and biofuels.
National Electric Energy Agency (Aneel)	Aneel is linked to the MME and regulates and supervises electricity generation, transmission, distribution, and trading.
The Federal Court of Accounts (TCU)	Responsible for accounting, finances, budget, and property oversight of public bodies and entities of the country for their legality, legitimacy, and best value.
Federal Prosecution Service (MPF)	The MPF acts on federal matters regulated by the Constitution and federal laws whenever public interest is involved. The MPF is responsible for ensuring compliance with the laws, including international agreements. Furthermore, the MPF acts as a guardian of democracy, ensuring respect for principles and rules that guarantee popular participation.
Sector Companies	Private companies operating in the Brazilian energy sector
Energy Research Company (EPE)	Public Company linked to MME, responsible for the development of energy planning studies
National Electric System Operator (ONS)	Responsible for coordinating and controlling the operation of electricity generation and transmission facilities of the national power grid, called the National Interconnected System (SIN).
Environmental Agency (EA)	A public agency (federal, state or municipal) responsible for licensing projects with significant environmental impact and/or activities using environmental resources.
Municipal authority	Responsible for the management of public services in the municipality.
National Indian Foundation (Funai)	Responsible for overseeing actions and projects that can affect Indigenous peoples
Public	Citizens or groups of citizens impacted or interested in the project.

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Actors	Attributions
National Institute of Historic and Artistic Heritage (Iphan)	Responsible for managing and preserving historic and cultural heritage
Palmares Cultural Foundation (FCP)	Responsible for preserving the heritage and socioeconomic viability of remnant communities of quilombos, remote communities formed by runaway slaves
Health Surveillance Secretariat (SVS)	An entity of the Ministry of Health responsible for minimising the incidence of communicable diseases, such as malaria and dengue fever
Conservation Areas (CAs) Agencies	Public agencies responsible for the management of environmental protected areas
National Department of Mineral Production (DNPM)	It aims to promote the planning and development of mineral exploitation

Source: Adapted from Cardoso Júnior et al. (2014).

2.2 TRANSMISSION POWER LINE CASE STUDY

We selected the Marimbondo II 500 kV project – Campinas and associated substations as a Brazilian case to apply the geographic modelling. The TPL was approximately 365 Km long (EPE, 2012) and aimed to provide electrical improvements to the southeast of the country through the connection of the UHE Belo Monte to the state of Minas Gerais (Ambientare Environmental Solutions and ATE XXII, 2014). Figure 2 illustrates the studied area, highlighting the electrical substations connected by the project, situated between the cities of Fronteira and Campinas.

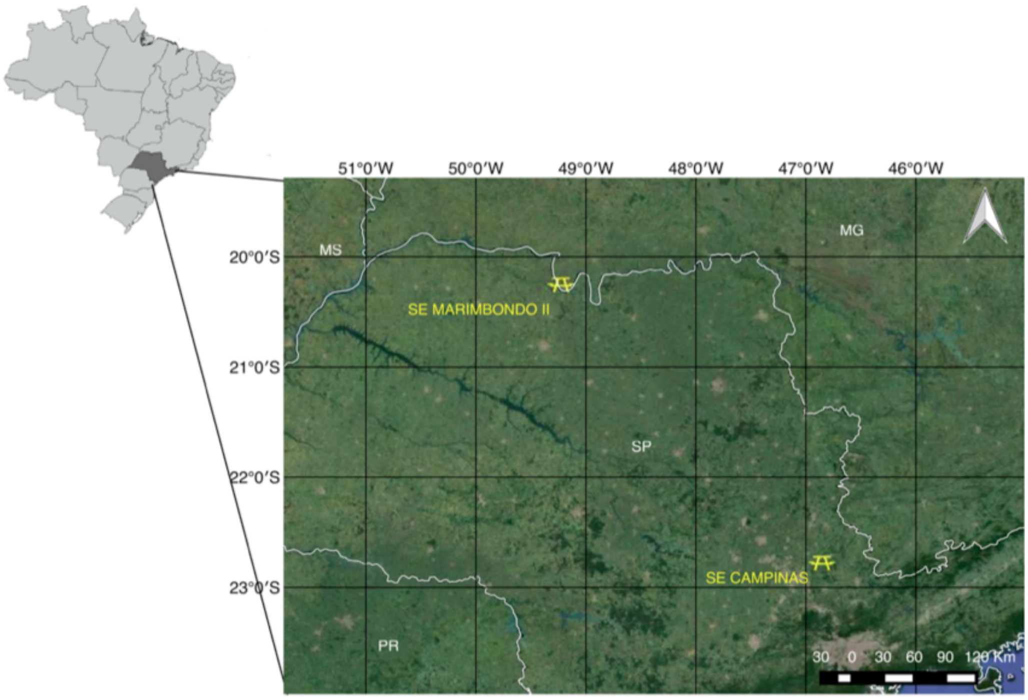

Figure 2 | Chosen study area for modelling: the 500 kV Marimbondo II – Campinas transmission line project and its related substations

Source: Autor's representation, background Google Earth ®.

This 500 kV project was proposed to provide electricity produced from the Belo Monte Dam hydroelectric power plant built in the north of the country, with an installed capacity of 11 GW, as part of the national plan to increase the electrical energy offer to Brazil's southeast region, which in turn demands projects of regional reinforcements in the power transmission (EPE, 2012). Marimbondo II is approximately 2,000 km away from Belo Monte Dam.

As presented in Figure 3, the depicted corridor spans approximately 20 km in width and 365 km in length, intersecting 32 municipalities and covering areas of savanna and semi-deciduous seasonal forest (EPE, 2012). It is worth mentioning that this project encountered challenges in its environmental licensing process, given its initial location overlapping with an area designated for airport expansion, an environmental legal reserve, and a zone earmarked for a free-flight project, tourism, and environmental conservation (Ibama, 2014).

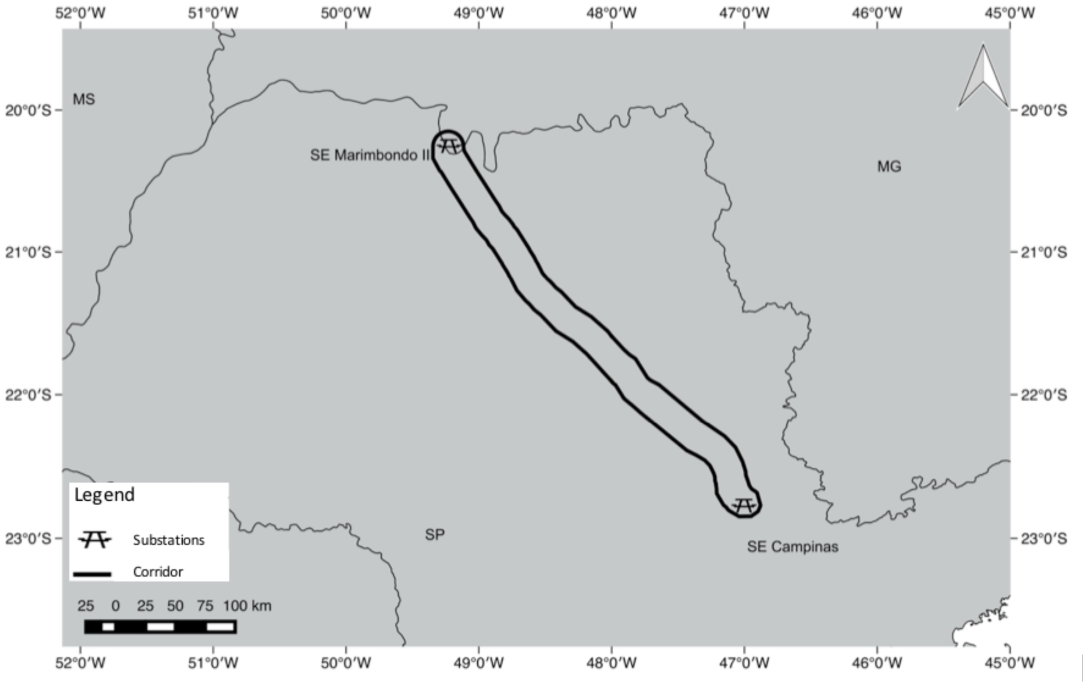

Figure 3 | The final corridor identified through the locational studies of the 500 kV Marimbondo II – Campinas transmission line project and its related substations planning..

Source: Autor's representation

3 METHODOLOGY

The model was developed according to the corridor approach advanced by Nóbrega *et al.* (2009), which integrates the Analytic Hierarchy Process (AHP) into the organisation of map algebra, thus enabling the determination of criterion weights. AHP is the most popular technique used in sustainable energy planning, especially for applications that aim to establish priorities and interaction with decision-makers (Araújo, 2016; Biassoto *et al.*, 2021; Ramachandran, 2004), therefore employed in the present work.

Thomas Saaty proposed AHP as a multicriteria approach founded on pairwise comparison for assigning weights to the criteria within a decision-making framework (Malczewski, 1999). The method assesses criterion pairs influencing the decision process and employs a hierarchical configuration to address problem-solving in formulating alternatives. In practice, the model is supported by three ranking levels, as illustrated in Figure 4. AHP is used as algebra preprocessor maps to formulate cost surfaces that will support the calculation of potentially lower cost alignments (Sadasivuni *et al.*, 2009).

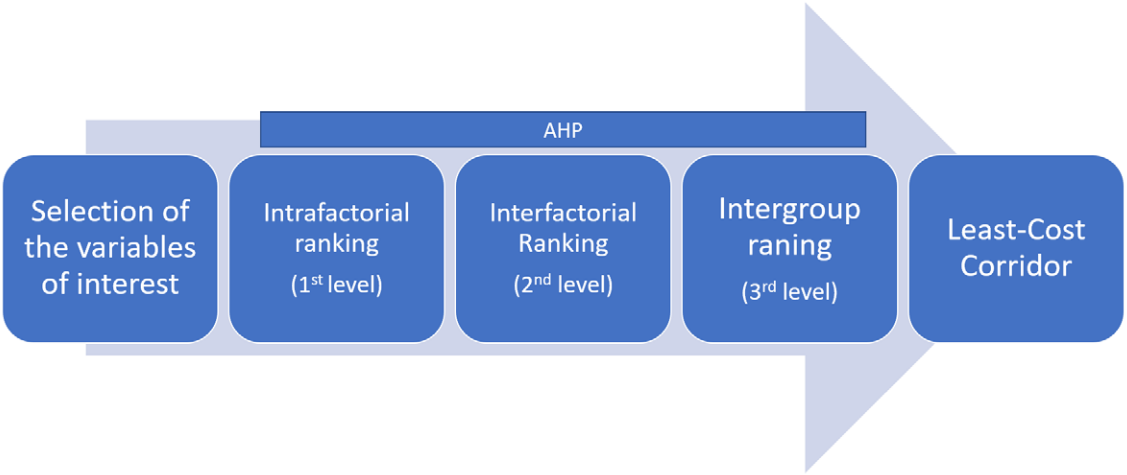

Figure 4 | The conceptual framework of the alternative corridor planning process is aimed at capturing the diverse values of the stakeholders and structuring the decision-making process into an analytical framework.

Source: Autor's representation.

Concerning the corridor approach, the conceptual model involves the computation of least-cost corridors based on spatial criteria facilitated by GIS techniques and multicriteria analysis (Sadasivuni *et al.*, 2009). The input data undergo thorough analysis, preprocessing, and organisation into spatial variables within the model. These variables are amalgamated with specific weighting roles to construct cumulative cost surfaces. Cost effort pertains to assessing each cell depicted in a map of weighting criteria, generating cost-surface maps (Van Leusen, 1998).

These maps, representing different variables of interest in a multicriteria analysis, are combined using map algebra to yield an accumulated cost surface. Cells with higher values indicate greater cost effort, implying a lesser preference for interception. Figure 5 illustrates the generation of a cumulative cost surface from individual cost surfaces derived from various information layers, each representing criteria considered in the decision process. Ultimately, the model employs a path algorithm from the final cost surface to determine lower-cost routes, yielding improved alternatives for connecting the specified points.

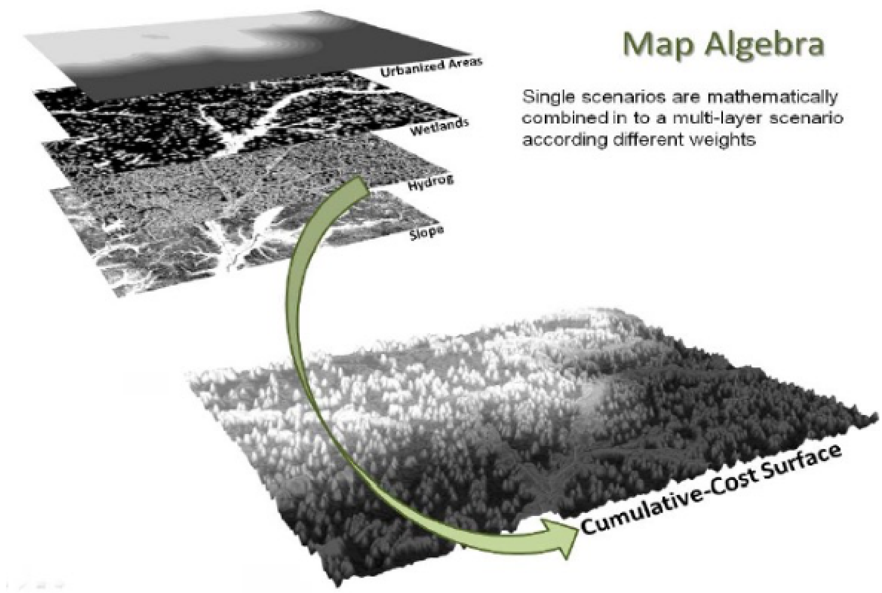

Figure 5 | Schematic aggregation of the cost surface through the integration of individual scenarios

Source: Sadasivuni et al. (2009).

Similar to the GIS least-cost path approach (Douglas, 1994), the corridor incorporates input variables and considerations to devise an optimised geographical solution for connecting origin and destination points. However, it is important to note that this approach does not impose a geometric design, which must be subject to local engineering analysis and decision-making (Nóbrega *et al.*, 2016). The geographical structure of the model, coupled with the multicriteria decision-making framework, allows for diverse solutions that can be tailored to different decision-making flows, including those related to Transmission Power Line (TPL) projects (Araújo *et al.*, 2021; Bagli *et al.*, 2011; Leon *et al.*, 2020).

The variables considered in the analysis were extracted from land cover, elevation, and vegetation, collectively called information layers (Nóbrega *et al.*, 2009). The process of selecting variables is inherently challenging, involving a literature review to identify variables influencing the study of transmission line alternatives, stakeholder interviews to determine pertinent variables for modelling and the availability of a suitable database at an appropriate scale for model execution. This study made efforts to incorporate as many variables as possible to assess the model's performance. The criteria followed established priorities, enabling a spatial analysis of combinations of factors and weights (Araújo, 2016). A total of 23 spatial variables that may impact TPL construction were selected, and Table 3 presents these variables along with their respective qualitative criteria.

Table 3 | Entities participating in the planning and licensing of transmission line projects within the Brazilian regulatory framework

	Variables	*Qualitative criteria*
Environmental variables	Protected Areas (PA)	Avoid interference in PA and their buffer zones
	Areas of permanent preservation (APP)	Avoid interference in APP
	Priority Areas for Biodiversity Conservation	Avoid interference in Priority Areas for Biodiversity Conservation
	Relevant areas for migratory bird	Avoid interference in Relevant areas for migratory bird
	Caves	Avoid interference in caves and their buffer zones
	Declivity	Avoid interference in a rugged/steep terrain area
	Parallelism with other linear projects	Proximity to other pre-existing linear projects
	Floodplain areas	Avoid interference in floodplain areas
	Native vegetation	Avoid Interference and fragmentation in areas with native vegetation
Social variables	Indigenous Lands	Avoid interference in Indigenous Lands
	Urban areas	Avoid interference in Urban areas
	Settlements	Avoid interference in settlements
	Quilombola territories	Avoid interference in quilombola (marrons) territories
	Areas of archaeological interest	Avoid interference in areas of archaeological interest
	Aerodromes	Avoid interference in aerodromes
	Visual impact	Minimise visual impact
	Areas of interest in mining	Avoid interference in areas of interest mining
	Areas of agriculture	Avoid interference in Areas of agriculture

Variables		Qualitative criteria
Economic variables	Areas requiring the installation of freestanding towers or tower elevation	Avoid interference in areas that require the installation of freestanding towers or tower elevation
	Floodplain areas	Avoid interference in floodplain areas
	Declivity	Avoid interference in a rugged terrain area
	Parallelism with other linear projects	Proximity to other pre-existing linear projects
	Areas needing the removal of vegetation	Avoid interference in areas needing the removal of vegetation

Source: Adapted from Cardoso Júnior et al. (2014).

The first level of the model is the intra-factorial ranking. The 23 variables are divided into three thematic groups: environmental, social, and economic. Qualitative general criteria and sub-criteria were defined for each variable. In order to get the prioritisation of each sub-criterion in terms of cost effort to implement a TPL, the AHP was applied to each variable. Based on priorities resulting from the AHP, each variable was structured as factors (maps in raster format), where the values of each pixel represent the cost of effort. Each factor represents an individual cost surface referring to a variable and its respective criteria. Figure 6 illustrates the result of the intra-factorial ranking of one environmental variable -terrain slope- where the conceptual criteria establish that the higher the slope, the higher the cost of the effort to build a TPL.

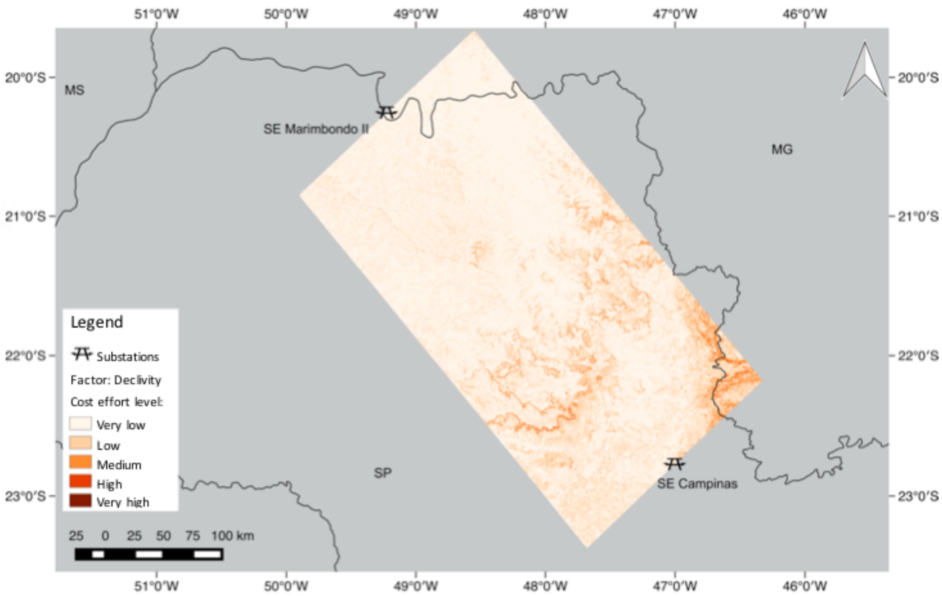

Figure 6 | Map derived from the intra-factorial ranking of the terrain slope factor

Source: Araújo (2016).

Drawing on the examination of the Brazilian decision-making flow outlined in section 2.1, the model's secondary and tertiary tier values are sourced from professionals affiliated with the organisations referenced in Figure 2. This strategic approach is designed to streamline the integration of a diverse array of stakeholders directly into the spatial decision-making process. The institutions actively involved in this process include the National Electric Energy Agency (Aneel), the Energy Research Company (EPE), the Federal Court of Accounts (TCU), and the Brazilian Institute of the Environment and Renewable Natural Resources (Ibama).

At the second level, accumulated cost surfaces are computed for each group of factors by multiplying the maps with their corresponding weights. These weights are derived from implementing the Analytic Hierarchy Process (AHP), involving consultations with 14 experts employed by the organisations mentioned above. The AHP aims to determine inter-factorial priorities within each thematic group, once again regarding cost effort.

In a parallel fashion, the third ranking level calculates an overarching cost surface, with AHP applied to the accumulated cost surfaces generated in the previous step. Based on this comprehensive cost surface, the model computes and presents lower-cost alternative corridors between two points of interest.

The resolution demands establishing the degree of importance among the criteria. This relative importance is commonly expressed numerically, often called weights (Biassoto *et al.*, 2022; Chakhar; Mousseau, 2008). The Analytic Hierarchy Process (AHP) ranks criteria through peer comparison regarding their importance, adhering to the fundamental scale of comparison developed by Saaty (Saaty; Vargas, 2001). However, the decision-making process does not conclude merely after obtaining the AHP pairwise inputs from consultations with various groups of individuals, including experts, politicians, and affected communities. In practice, it is also imperative to integrate the results in a balanced way.

Forman and Peniwati (1998) delineate two methods for deriving the overall priority of elements in a group decision process: Aggregation of Individual Judgments (AIJ) and Aggregation of Individual Priority (AIP). AIJ is applicable when groups harmonise their judgments to function as a collective entity, while AIP is suitable when individuals in the group act independently with distinct value systems and no shared goals or objectives (Araújo, 2016). The fundamental distinction between the two approaches lies in the behaviour of the groups involved in the decision-making process. If the group can be treated as a unified individual due to synergy among its components, weights are calculated by AHP from a matrix where paired classifications represent the geometric mean of individual classifications. Conversely, if the group lacks common goals and objectives, weight calculation is determined by the geometric or arithmetic mean of weights obtained from each individual (Forman; Peniwati, 1998).

This study aims to showcase the model's effectiveness by integrating actors participating in the decision-making process of new projects and considering their knowledge profiles. Environmental and social factors are provided by EPE and Ibama specialists, economic factors are provided by Aneel and TCU specialists, and all specialists provide inputs for intergroup ranking. Weight consolidation incorporates both the AIJ and AIP methodologies. The AIJ technique computes weights among specialists within each group, considering collaborative teamwork. Subsequently, the AIP approach is applied to the results obtained since each institution holds its values, knowledge, and objectives regarding studying a preferred corridor. Figure 7 illustrates the sequential steps' structure with the application of map algebra and corridor calculation.

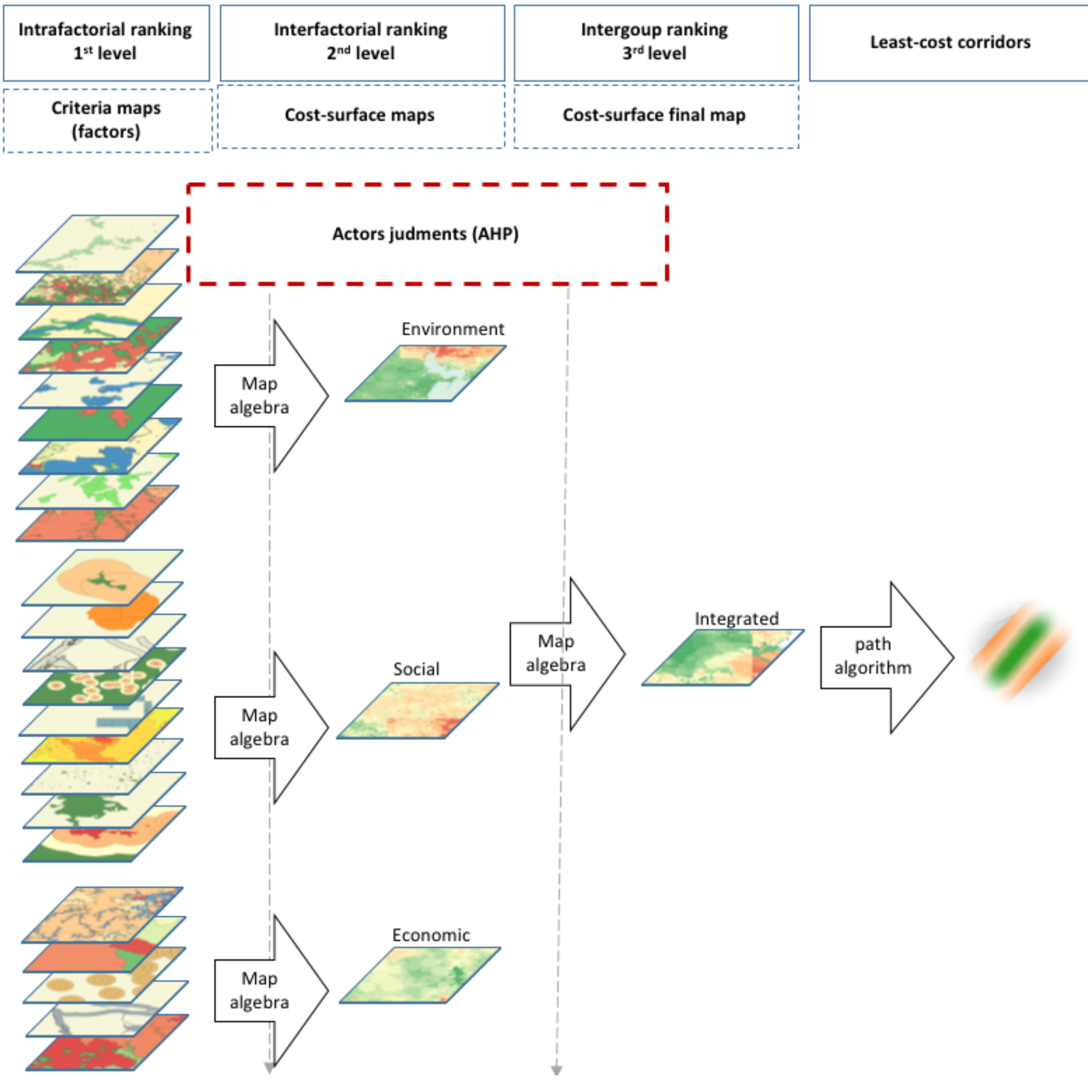

Figure 7 | Proposed multicriteria geographic intelligence aiming to integrate data, roles, and actors towards the sustainable planning of power transmission lines

Source: Araújo (2016).

4 RESULTS AND DISCUSSIONS

The application of AHP in problem structuring facilitates the integration of previously discussed variables, utilising its hierarchical structure centred on sustainability pillars. Actor weighting within the Brazilian regulatory model aligns with their respective stakes. Furthermore, the model's flexibility in accommodating diverse decision contexts allows for the inclusion of additional variables in the analysis. However, limitations arise from data accessibility and the selection of spatially influential factors. Configuring the model based on the diagnostic decision flow involves tailoring it with various actor levels and determining the dominant impact of the variable group. This adaptability is evident in the model's potential hierarchical expansion, reflecting the decision-making structure within its application context.

The detailed results in this section are sequentially and constructively organised. The context includes tables resulting from inputs provided by the consulted stakeholders and the ranking derived from the AHP process, followed by a series of illustrations depicting the progressive outcomes of the model compilation.

Since the research did not provide previous training for the developed classification (in fact, out of the 14 experts, only one had any experience working with AHP), results affirm the simplicity and ease of understanding of the paired classification method applied in the AHP (Wang *et al.*, 2009). Nevertheless, participants provided a consistent output in their classifications. The AHP calculates the Consistency Rate (CR) from a matrix algebra based on pairwise comparisons. It signifies the consistency of weights given by experts. Consistency is established if TC < 0.100; otherwise, the proportion is inconsistent and requires further development until it reaches consistent levels. Table 4 presents the CR values from the expert's inputs (participants), demonstrating the judgments' consistency.

Table 4 | Rates of consistency derived from experts' classifications using AHP

	Classification			
Consistency Ratio (Experts)	Interfactorial Ranking: Environmental criteria	Interfactorial Ranking: Social criteria	Interfactorial Ranking: Economic criteria	Intergroup ranking
E1	0.089	0.073	0.098	0.057
E2	0.075	0.088	0.098	0.000
E3	0.095	0.099	0.078	0.025
E4	0.035	0.019	0.029	0.000
E5	0.098	0.094	0.054	0.033
E6	0.004	0.095	0.099	0.000
E7	0.069	0.067	0.041	0.057
E8	0.017	0.048	0.079	0.000
E9	0.071	0.047	0.009	0.033
E10	0.061	0.066	0.071	0.056
E11	0.036	0.019	0.000	0.000
E12	0.029	0.053	0.073	0.025
E13	0.051	0.063	0.095	0.056
E14	0.037	0.076	0.091	0.000

Source: Author's calculation.

After completing the aggregation of judgments and priorities, as detailed in section 3, numerical values supporting the modelling are obtained. The intergroup sensitivity analysis reveals a balance among groups of factors in the model, with a slightly greater influence of the economic factor. The aggregation of values, guided by AIJ and AIP, operates with geometric means, enhancing the coherence of experts' judgments. In this approach, consulting the same number of experts from different stakeholders is not mandatory, as the JIA and AIP approach calculates and applies an average of the values. Figures 8, 9, 10, and 11 illustrate the resulting sensitivity analyses.

Commenting on the cross-applicability of the values discovered in this sensitivity analysis proves challenging. Since the cross-applicability relies on consultations with experts from institutions with a vested interest in the decision-making and is specifically tailored to the project under examination, varying results might arise with the participation of different experts or other stakeholders, particularly when applied to a different project. In essence, this methodology phase necessitates development for each distinct modelling, at least until applied research on the variables of interest and their relative importance in formulating locational alternatives for TLP is undertaken.

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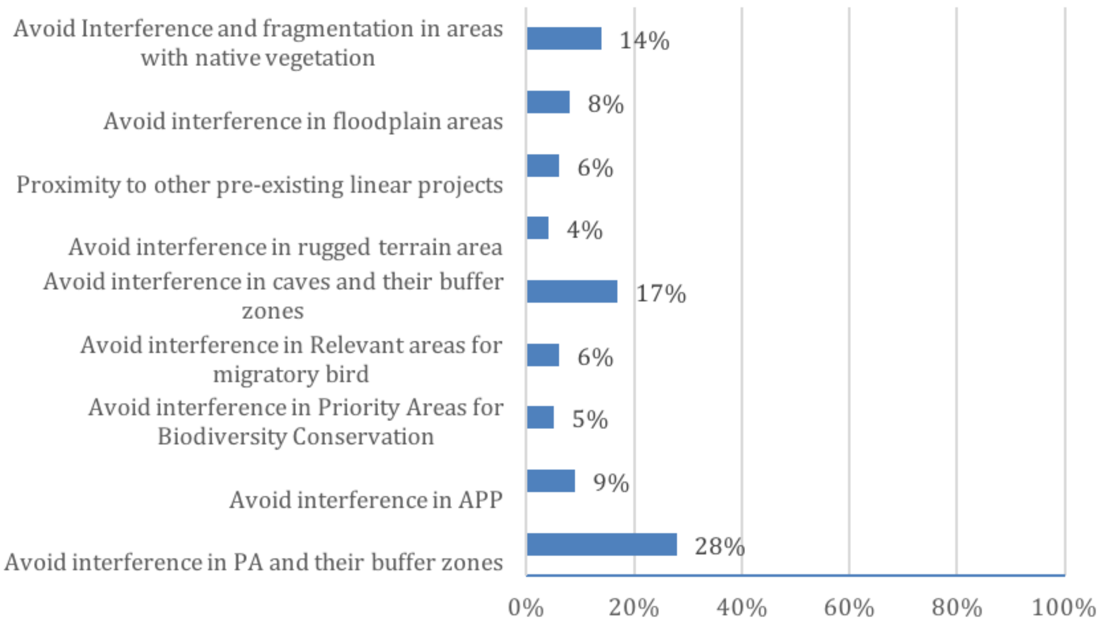

Figure 8 | Sensitivity analysis of the inter-factorial rank of the group of environmental factors

Source: Araújo (2016).

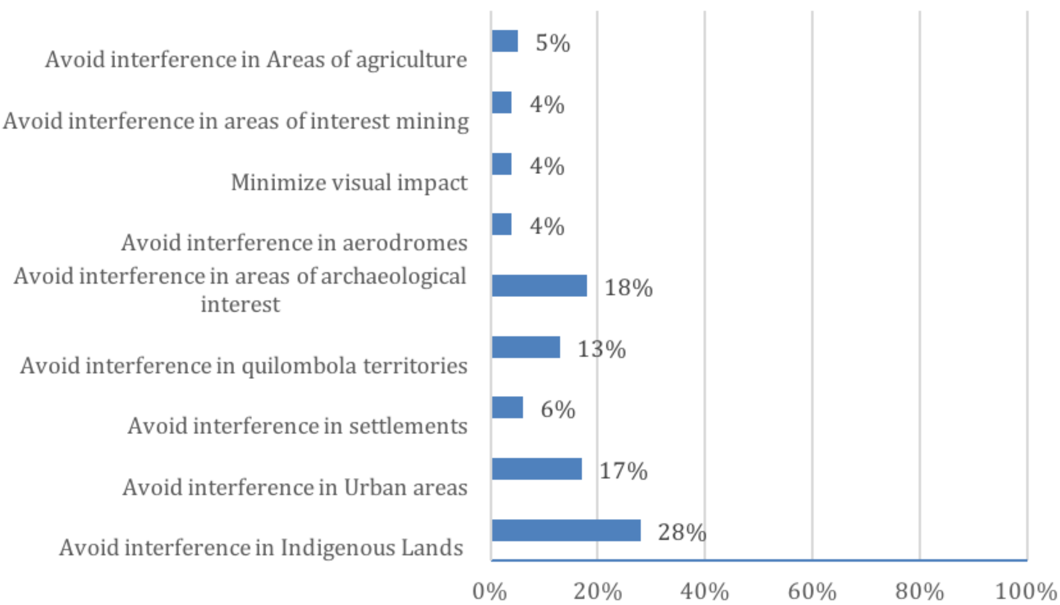

Figure 9 | Sensitivity analysis of the inter-factorial rank of the social factors group

Source: Araújo (2016).

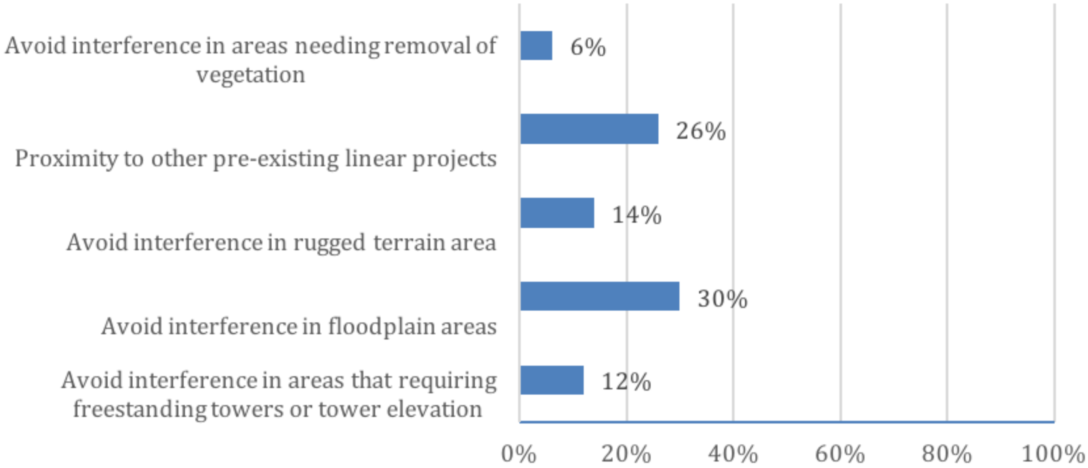

Figure 10 | Sensitivity analysis of the inter-factorial rank of the group of economic factors

Source: Araújo (2016).

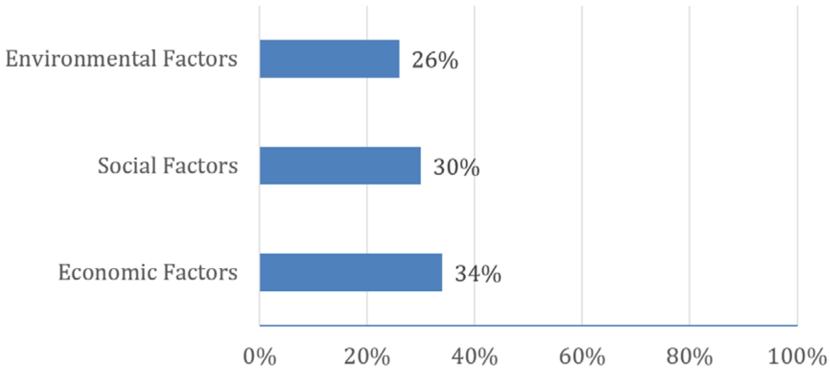

Figure 11 | Combined sensitivity analysis of intergroup ranking

Source: Araújo (2016).

Figure 12 presents the map of corridor alternatives derived from the modelling, incorporating the selected variables and the expert classifications. The alternatives are represented on an effort cost gradient, with the least cost of effort (preferred) shown in green, while other colours denote varying preference levels. The black line represents the corridor resulting from the planning studies, serving as a reference for the auction stage and environmental licensing. The model highlights a preferred alternative for decision-makers and presents other viable choices as the project progresses through its phases. Researching alternative corridors aims to support the project's planning and development. As the project progresses to executive phases and the definition of spatial data scale, including field trips and social participation, additional elements may surface, influencing decision-making. Given that a TLP occupies an area between 30 and 100 meters wide, depending on electric voltage, alternatives with slight differences in total length become crucial for final decision-making. The results also guide the project's engineering toward a more sustainable alternative, incorporating inputs from stakeholders earlier in the regulatory process than they would typically be involved.

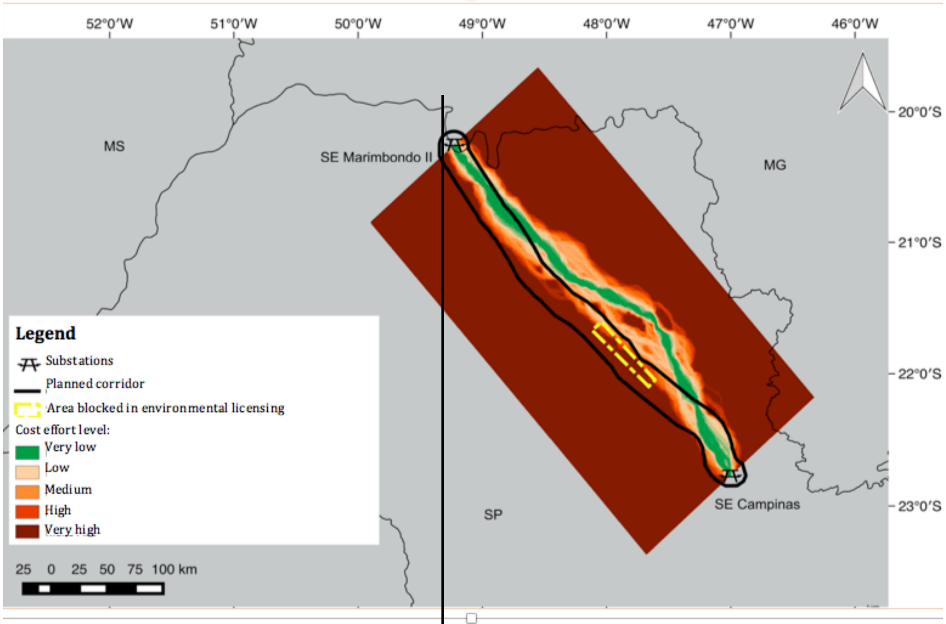

Figure 12 | Outcome derived from the feasibility corridor modelling for the transmission power line

Source: Araújo (2016).

The model operates without a predetermined number of alternatives or a fixed corridor width. Adapted to the spatial features of the studied region and criteria classifications, the model explores various alternatives with distinct levels of effort cost. For instance, the study's outcomes reveal a notable divergence in alternatives near the midpoint due to the presence of a protected area in the region. Figure 13 displays the individual cost surface map for the environmental protection areas, highlighting the region influencing the noted divergence. According to the modelling, this characteristic better captures the intricacies of the modelled real-world scenario, enhancing decision-making by enabling a focused allocation of efforts in areas previously identified as more viable.

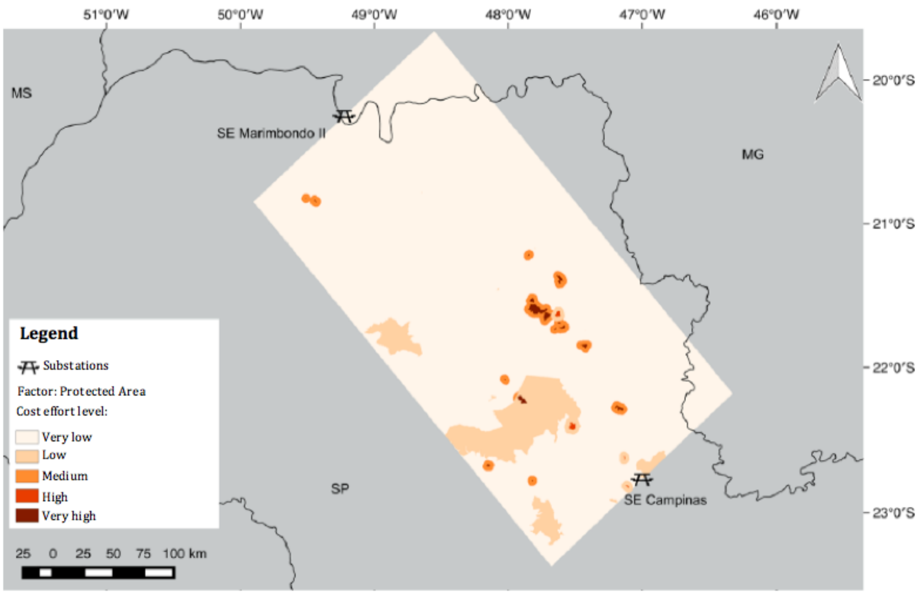

Figure 13 | Map resulting from the intra-factorial ranking of the factor associated with protected areas

Source: Araújo (2016).

Comparison with the corridor outlined during the planning phase reveals that the modelled corridor avoids interference with the problematic yellow segment, which has posed challenges in securing environmental licensing for the project. Notably, the results exhibit trends contrary to the official corridor, especially in the vicinity of SE Campinas, where it refrains from intersecting the yellow region. An examination of the individual cost maps for the variables considered in the modelling indicates that this divergence is attributed to the criterion of non-interference in urban areas, precisely addressing the concerns related to the yellow region. The environmental agency's technical team responsible for licensing the project attributes the obstruction to the potential impact on the planned free flight, tourism, and environmental conservation project in the Municipality of Taguaritingal (Ibama, 2014).

This outcome underscores the potential for identifying and addressing future issues during the designation of a right of way for TPL. Notably, this concern only surfaced during the environmental licensing phase of the power line, after planning studies and the auction. Figure 14 provides a visual representation of this analysis, depicting the overlap between the corridor studied during the planning stage, the contested segment in environmental licensing, and an individual cost surface for urban areas. While enhancing the TLP planning process is imperative, it is important to acknowledge that limitations constrain the approach and heavily depend on the availability of up-to-date and official geographic data.

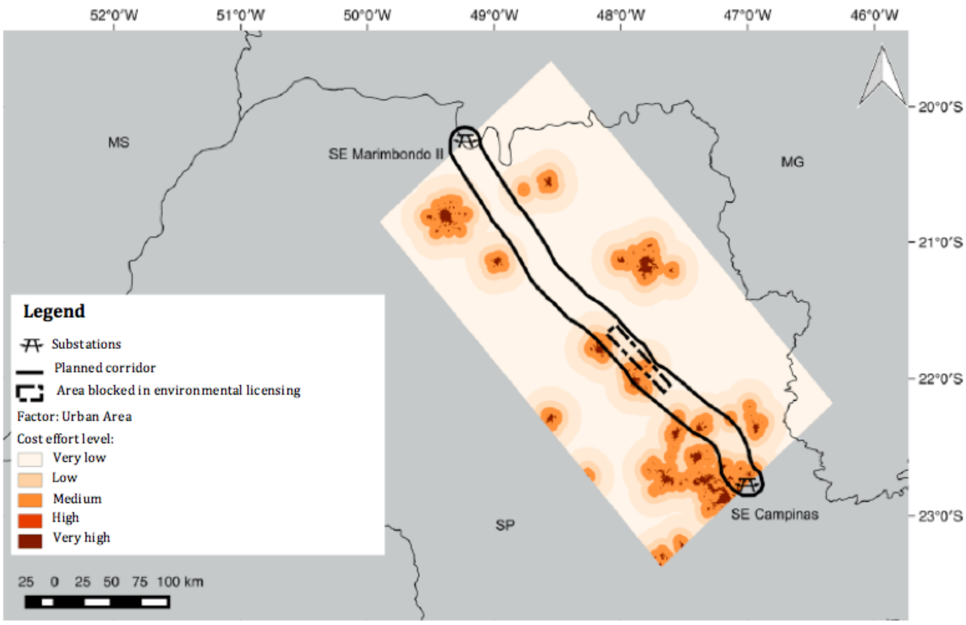

Figure 14 | Overlaying the corridor studied in the planning stage, the contested segment in the environmental licensing, and the distinct cost surface related to urban areas

Source: Araújo (2016).

Finally, the examination of the generated alternatives illustrates the model's capacity to (i) delineate lower-cost alternatives for connecting the origin and destination points, (ii) circumvent expansive areas categorised as medium and high effort cost, situated near the line connecting the two analysed points; and (iii) steer clear of regions with overlapping spatial factors, contributing to increased effort costs, such as areas where native vegetation and slope criteria intersect.

5 CONCLUSIONS AND POLICY IMPLICATIONS

In conclusion, the research sheds light on opportunities to enhance the evaluation of environmental concerns in planning new transmission power lines (TPL) in Brazil. The current regulatory model, primarily focused on technical and economic factors, demonstrates limitations in addressing social and environmental considerations comprehensively. The environmental licensing stage, the primary interface with society, occurs after crucial decisions have been made, hindering meaningful stakeholder participation.

The proposed multicriterial spatial modelling approach aims to overcome these limitations by providing a holistic corridor design early in the TPL planning. The model, developed through collaboration with stakeholders from various organisations, showcases its ability to integrate diverse perspectives and anticipate social and environmental demands throughout the decision-making process. Its strength lies in simplifying complex decision flows in energy policy structures while offering transparent and comprehensive results.

The model's presentation of alternative gradient maps, rather than a fixed corridor, enhances information dissemination and knowledge levelling among stakeholders, contributing to more informed decision-making. Despite the model's subjectivity, it is a valuable tool for informing top-down decisions about project viability. Recognising its limitations, such as reliance on spatialisable variables, the model holds significant potential to qualify decision-making processes in complex energy policy scenarios involving new TPL projects.

The model could modernise the TPL planning process by optimising the initial corridor to a few hundred meters during the engineering construction phase. Moreover, there is potential for future research to explore public participation, further democratising the decision-making process in energy infrastructure projects.

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