

# Supporting Regional Airport Planning in Brazil via Analytic Hierarchy Process

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## ABSTRACT

The objective of this study was to evaluate a shared regional airport site for Pato Branco and Francisco Beltrão, Paraná, Brazil, using airport site selection methodology. Ten sites were identified within a 550 km<sup>2</sup> search area. Five were excluded because of obstacle or infrastructure constraints; the remaining sites were surveyed and ranked using the analytic hierarchy process. Thirty-three federal, academic, and regional experts assessed the criteria independently, and 18 judgments met the prescribed consistency threshold. Group priorities were compared using exploratory Wilcoxon–Mann–Whitney's tests, and weight sensitivity was assessed one criterion at a time. Sites 2, 2C, and 2A were the three highest-ranked alternatives under every group-specific weighting scheme. The regional group assigned greater weight to earthmoving volume and land access than the federal and academic groups. Earthmoving volume accounted for 25–67% of the global weight, whereas the noise criterion did not discriminate among the sites. The conclusion was that the three-site short list was stable across stakeholder groups and more stable than its internal ordering.

**Keywords:** Regional aviation; Airport planning; Site selection; Multicriteria analysis; Sustainable urban mobility; Analytic hierarchy process.

## INTRODUCTION

Regional aviation connects small and medium-sized Brazilian cities to major urban centers and provides access to remote and border regions (Oliveira and Silva 2008). Airport investments may be funded by federal resources, agreements with states or municipalities, public entities, or private concessions and authorizations (República Federativa do Brasil 1986). Because site selection affects construction cost, environmental licensing and operational viability, the criteria and their relative importance should be specified before alternatives are compared.

International Civil Aviation Organization (ICAO 1977) guidance identifies airspace protection, meteorological conditions, soil and drainage, utility services, surface access, expansion capacity and proximity to demand among the factors relevant to airport siting. No candidate normally performs well on all the factors. Multi-criteria decision analysis (MCDA) provides a structured means of combining measured performance with stated preferences and of documenting the resulting trade-offs (Gomes 2007; Gomes *et al.* 2004). MCDA methods differ in how preferences are elicited and combined (Salgado *et al.* 2011).

Among these methods, the analytic hierarchy process stands out, having been successfully applied in selecting regional airport sites, as demonstrated in both the Samothraki Island case by Ballis (2003) and the study conducted by Sennaroglu and Celebi (2018). More recently, the AHP method has expanded into new frontiers of air mobility, notably in developing frameworks for classifying potential cities for implementing emerging urban mobility technologies, particularly electric vertical take-off and landing aircraft, as discussed by Spühler *et al.* (2025).

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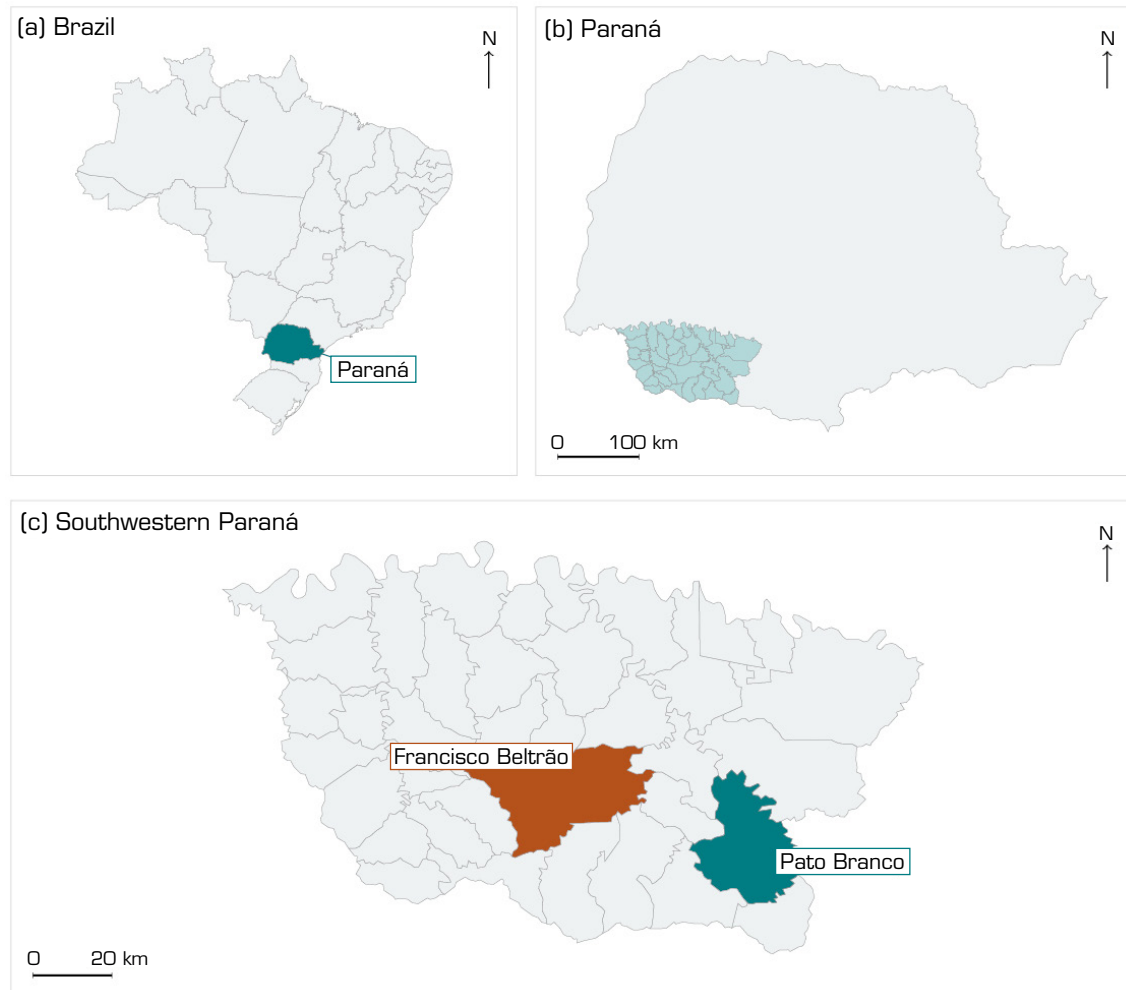
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AHP has also been applied to urban mobility assessment (Di Lorenzo *et al.* 2025) and to the ranking of cities for emerging air-mobility technologies (Spühler *et al.* 2025).

This study applied the airport site selection methodology (MESA), which combines geographic information systems with AHP (Alves *et al.* 2020), to a shared airport for Pato Branco and Francisco Beltrão, in southwestern Paraná, Brazil (Fig. 1).



Location of Pato Branco and Francisco Beltrão in southwestern Paraná, Brazil. (a) Paraná within Brazil. (b) Regional context within Paraná. (c) The municipalities of Francisco Beltrão and Pato Branco, highlighted within the Sudoeste Paranaense mesoregion. Source: IBGE simplified geographical boundaries (2020). Municipal and regional boundaries provide geographical context and do not delimit the airport search area. Local equirectangular projections; scale bars are approximate.

**Figure 1.** Southwestern region of the state of Paraná, Brazil.

## Contributions

The methodology was proposed by Alves *et al.* (2020). This study is an empirical application and analysis rather than a modification of MESA. Its contributions are:

- Reproducible reporting: The individual priority vectors and consistency ratios of all 33 experts, the raw and normalized site metrics, and the final scores are reported so that the ranking can be recomputed from the article. This 2018–2019 case was the first operational application of MESA and, to our knowledge, is the first fully reported application of MESA in peer-reviewed literature;
- Group-disaggregated results: Separate federal, academic, and regional priority vectors show stakeholder groups' convergences and divergences;

- Consistency evidence: Inconsistent judgments occurred in 33% of the academic, 36% of the federal, and 62% of the regional participants. Evidence from two additional MESA applications is used to examine whether this pattern may be associated with participants' experience with formal decision procedures;
- Drivers and sensitivity: Global weights identify the criteria that determine the ranking, and a one-at-a-time sensitivity analysis distinguishes the stability of the three-site short list from that of its internal ordering.

The paper is organized as follows. First, there is a review of multi-criteria decision analysis, and AHP is positioned within it. Later, MESA is described phase by phase, including the AHP formulation used in its final phase. The next section applies the methodology to southwestern Paraná, following the same phase structure, so that method and application can be read side by side. Then, we bring the discussion of the results and the limitations of the exercise, before the conclusion of the paper.

## Background

This section situates the problem within the multi-criteria decision analysis literature and explains why AHP was the method adopted by MESA. The mathematical formulation of AHP is deferred to the subsection "Phase V: Prioritization of candidate sites," in which it is presented as part of the phase in which it is actually used.

### *Airport site selection as a decision problem*

The importance of air transport is indisputable, as aviation represents one of the most dynamic sectors of the global economy and responds directly to fluctuations in political and economic conditions. Additionally, it promotes the exchange of people and goods, strengthening economic relations among regions.

However, for air transport to achieve its social, environmental, and economic objectives, selecting optimal locations for airport construction becomes crucial. This selection task constitutes a complex decision-making problem, requiring the evaluation of multiple criteria to adequately choose from among available alternatives.

Moreover, certain trends have prevailed in airports and the aviation industry in the early 21st century (Sennaroglu and Celebi 2018): long-term growth of approximately 5% per year globally, resulting in traffic doubling every 15 years, thus requiring continuous expansions and improvements; commercialization, characterized by increasing business management within a market economy replacing state ownership in a regulated environment, a trend that makes economic performance and efficiency essential criteria for project success, along-side conceptual changes; and globalization, evidenced by alliances among transnational airlines and airport managers, indicating the implementation of global best practices in providing airport services.

In this context, Brazil's Regional Aviation Development Program (PDAR), launched at the end of 2012, envisioned an investment of R\$ 7.3 billion in 270 regional airports to increase the number of routes operated by airlines, integrate new airports into the regular air transport network, and expand the Brazilian population's access to air services. From the perspective of PDAR, expanding the airport network would contribute to national territorial integration, strengthening tourism hubs, developing regional poles, and ensuring access to communities in the Legal Amazon. Consequently, it was anticipated that 96% of the population would be located within at least 100 km of a passenger terminal. At the beginning of 2018, however, approximately 40 million people in Brazil were situated further than this distance from an airport (Brasil 2018).

Given the above, the necessity for decision-making tools becomes evident when expanding a country's airport network. Generally, two scenarios emerge: either the existing airport infrastructure cannot be expanded, making continued operations in the same location unfeasible, or the locality lacks an aerodrome altogether. The case reported in this article is of the first kind: both cities have small aerodromes constrained by urban growth, and the regional consortium sought a single new site able to serve them jointly.

Thus, airport site selection emerges as a complex decision-making problem, demanding the evaluation of various criteria to make a final choice among different alternatives. In this scenario, MCDA appears as an important tool, standardizing the decision-making process through mathematical modeling and assisting decision-makers in solving problems that involve achieving multiple objectives simultaneously.



In summary, using a multi-criteria decision tool offers benefits such as quantification, reducing subjectivity by assigning numerical values to criteria; comparability, allowing systematic evaluation of different sites using a common basis; and decision transparency, making explicit the factors considered and their relative weights. These aspects facilitate communication with stakeholders and authorities. Additionally, auditability allows tracking of decisions and their technical justifications, crucial in public infrastructure projects, and adaptability enables adjustments as new information or regulatory requirements emerge.

## Multi-criteria decision analysis

Multi-criteria decision-making problems are characterized by having at least two objectives that cannot be achieved simultaneously. Regarding the selection of regional airport sites, these problems are particularly complex. Most decisions involve multiple objectives, multiple decision-makers, and are subject to external review.

According to Giuliano (1985), a disciplined and transparent decision-making process should have: a structured approach to complex problems; a clear rationale for decisions; consistency throughout the decision-making process; objectivity; documented hypotheses, criteria, and values utilized in decision-making; and, ultimately, decisions that are replicable, subject to review, and easily comprehensible.

Usually, none of the alternatives is the best regarding all objectives; hence, the one that best approximates the objectives can be selected based on certain evaluation criteria (Bhushan and Rai 2004). These criteria should be defined according to the objectives, must be capable of differentiating between alternatives, and assist in choosing the one that best fits the decision-maker's preferences. Each criterion should measure a significant characteristic and be independent of the others. Generally, criteria must be capable of differentiating between alternatives; comprehensive enough to cover all objectives; non-redundant; operationally clear, allowing the decision-maker to understand the implications of the alternatives; and numerically limited, to keep the problem dimensions manageable (San Cristóbal Mateo 2012).

It is important to emphasize that criteria can encompass both subjective and objective dimensions. Decision-makers' subjectivity arises from individual perceptions and must be considered in the decision-making process. The model must accurately reflect the decision-maker's true preferences (Sabaei *et al.* 2015).

During the structuring of the decision-making process, it is essential to comprehend the context in which the decision occurs. The nature of the problem guides the choice of the multi-criteria method to be applied. Tsoukiàs (2008) identifies four types of problematics:

- The selection problematic, in which the best alternative or subset of alternatives is chosen by comparing potential actions;
- The classification problematic, in which each potential action is assigned to a predefined class;
- The ranking problematic, which orders potential actions in a hierarchy;
- The description problematic, which describes and reports the consequences of potential actions.

More than one type may be present in a single problem. Airport site selection as posed here is primarily a ranking problematic: the deliverable requested by the public authority is not a single site but an ordered short list, from which the final choice is made after complementary environmental and economic studies.

The literature offers numerous methods and applications of MCDA, the selection of which depends on the nature of available information. Generally, these methods are grouped into three broad categories: multi-objective mathematical programming, multi-attribute utility theory, and outranking methods (Roy 1996). AHP, created by Thomas L. Saaty in the 1970s (Hwang and Yoon 1981; Saaty 1990), belongs to the second category. MESA adopts it for three practical reasons. First, it decomposes the problem into a hierarchy, which lets a decision be discussed at the level of broad concerns (which matters more, the airport or the city?) before descending to individual criteria. Second, it elicits preferences through pairwise comparisons, a task that non-specialist participants such as municipal technicians can perform without training in decision theory. Third, and decisively for a public procedure, it provides a consistency measure that allows internally contradictory judgments to be detected and set aside using an explicit, auditable rule rather than a subjective assessment of who is qualified to judge.

## The airport site selection methodology

Given the complexity of decision-making in selecting airport sites, the team from Brazilian Instituto Tecnológico de Aeronáutica (ITA), in partnership with the Civil Aviation Secretariat (SAC), developed MESA. This structured approach aims to identify and evaluate feasible areas for regional airport implementation while standardizing analysis criteria and enhancing objectivity in the decision-making process (Alves *et al.* 2020).

In Brazil, the selection of new sites for regional airport development often faces significant challenges due to the occupation of surrounding areas and the exhaustion of available space at existing aerodromes, which limits the feasibility of renovations or expansions. To address these issues, SAC and ITA jointly produced the Manual for Supporting the Prospection of Regional Airport Sites (Brasil 2021), approved by Ordinance No. 837 of July 13, 2021, and in force since September 1<sup>st</sup>, 2021. The manual is organized in six chapters: the first five correspond to the site selection workflow described below, and the six one prescribes the deliverables of the process, namely the prospection report and the georeferenced database in digital form.

This document presents MESA (from the Portuguese *metodologia para escolha de sítios aeroportuários*), which guides the site selection process based on broad and well-defined technical criteria. Importantly, according to SAC/Ministério da Infraestrutura guidelines, any proposal for the construction of a new regional airport seeking public funding must mandatorily follow MESA to be eligible for financing.

## Two different sets of phases

A clarification is needed before the phases are described, because the same methodology is presented elsewhere with a different number of stages. In Alves *et al.* (2020), MESA is introduced through four phases:

- A literature review of airport site selection criteria;
- The systematization of those criteria;
- The definition of eliminatory criteria and their thresholds;
- The definition of scoring criteria and of how to quantify them.

Those four phases describe how the methodology was built; they are designed as steps, performed once by the research team, and their output is the methodology itself.

The five phases described below are of a different nature. They constitute the *application* workflow, the sequence a planning team follows each time MESA is used in a new region, and they are the ones prescribed by the official manual. The eliminatory criteria fixed in design phase 3 are what phases II and III apply on the ground; the scoring criteria fixed in design phase 4 are what phase V weights and combines. The two sets are therefore complementary rather than alternative, and it is the second one that structures this paper.

### *Phase I: Basic requirements and search area delimitation*

In this initial phase, fundamental project parameters are established, including the definition of demand-generating centers (CGDs), the design aircraft, operational requirements, and the initial search area boundaries. Preliminary sizing of the site and its spatial orientation are also determined at this stage, considering meteorological data, altitude, and regional wind patterns.

### *Phase II: Reduction of the search area*

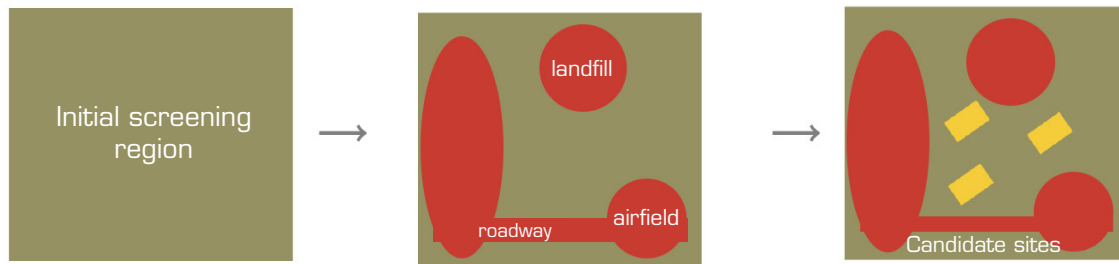
This phase involves applying exclusionary criteria through geoprocessing techniques. A standardized georeferenced database is developed containing information about environmental preservation areas, proximity to other airfields, urban centers, landfills, and other restrictive elements. Overlaying these information layers results in a map indicating potentially viable areas.

### *Phase III: Identification of candidate sites*

From the viable areas identified in the previous phase, analyses are conducted to identify specific sites with suitable geometry to accommodate an airport. Issues such as altimetric variation within the physical site area and potential airspace obstacles are evaluated during this phase. These two criteria are exclusionary, helping eliminate unsuitable candidate areas.

Figure 2 summarizes how phases I to III progressively narrow the territory: an initial screening region is defined, restrictive layers are overlaid to remove infeasible land, and candidate sites with adequate geometry are then positioned within what remains.





Source: adapted from the process described in Alves *et al.* (2020).

**Figure 2.** Progressive reduction of the search area in airport site selection methodology (MESA): (a) the initial screening region defined in phase I; (b) restrictive layers overlaid in phase II, which exclude conservation areas, landfills, the vicinity of other airfields, roadways, and similar constraints; (c) candidate sites of adequate geometry positioned in the remaining feasible land in phase III.

#### Phase IV: Fieldwork

Candidate sites are visited to validate remotely obtained data and collect additional information. Geotechnical surveys, precise identification of possible obstacles, conflicting activities in the surroundings, and other relevant features inadequately assessed in previous phases are conducted.

#### Phase V: Prioritization of candidate sites

In this final phase, which is the primary focus of the present work, candidate sites are evaluated and ranked using AHP. This phase comprises three stages, described in the following subsections.

##### Stage 1: Expert groups and criteria weights

Three multidisciplinary groups of experts are formed to conduct pairwise judgments among the established decision criteria:

- Regional group: composed of municipal and state technicians who have detailed knowledge of the region;
- Federal group: constituted by experts from SAC and National Civil Aviation Agency, representing the technical staff of the Brazilian federal government;
- Academic group: composed of ITA specialists.

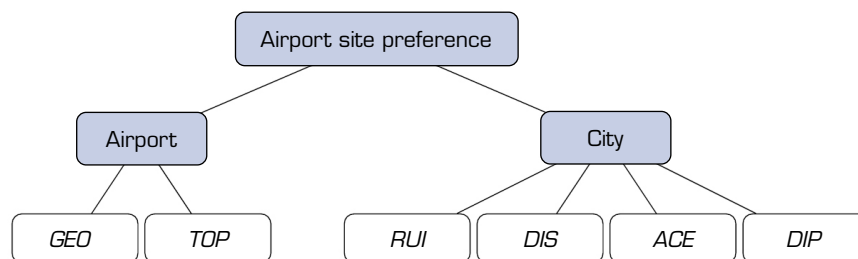
Each group performs its own AHP process, and subsequently, an individual aggregation of priorities (IAP) is conducted to obtain the final priority vector. The IAP is the simple arithmetic mean of the individual priority vectors of the experts retained after the consistency filter (Brasil 2021). This approach is significant as it enables all stakeholders involved in the project to participate in the decision-making process, thereby making the priority vector as unbiased as possible and eliminating potential local authority preferences in site selection.

Two procedural safeguards are prescribed for the elicitation. Experts are heard individually rather than in a group, so that priorities are not shaped by deference within the panel, and they must not be shown the set of candidate sites before delivering their judgments, since knowing the alternatives could lead a respondent to choose weights that favor a preferred site rather than to state what genuinely matters. A facilitator appointed by the prospection team provides information about the region and about the technique, with the explicit aim of reducing the incidence of inconsistent judgments (Brasil 2021). The criteria considered by MESA include accessibility, distance to demand-generating centers, availability of public services, noise impact, earthmoving volume, and geotechnical conditions. The description and metrics adopted for each classification criterion are detailed below:

- Geology, GEO (higher is better): refers to the soil characteristics (resistance and stability) and its influence on the construction of runways, aprons, and airport buildings. It is calculated as the arithmetic mean of the highest soil penetration resistance measured by the dynamic cone penetrometer (DCP) test up to 3 m depth, performed at three points of the potential site (near each runway threshold and near the runway midpoint). The DCP readings, in mm per blow, are converted into California bearing ratio (CBR) values through the standard correlation, so that the criterion is reported on a scale familiar to pavement engineers. The resulting figure is a proxy for the bearing capacity of the natural, uncompacted soil;

- Topography, TOP (lower is better): refers to the impact of earthmoving volume (resulting from altimetric variation at the potential site) associated with airport construction. It is calculated by the volume of earth (in m<sup>3</sup>, including both cut and fill) between the natural terrain and the airport runway strip, considering this strip positioned horizontally at the average elevation of the terrain along the most favorable axis for runway placement at the considered potential site;
- Noise and Urban Zoning, RUI (lower is better): refers to noise disturbance caused by airport operations in adjacent and nearby areas. This evaluation counts the number of buildings within the 65 dB contour, as defined by the basic noise zoning plan stipulated in National Civil Aviation Agency's aviation regulation 161;
- Distance to Demand-Generating Center, DIS (lower is better): refers to the effective distance from the potential site to a reference point associated with the city's CGD. This center is represented by landmarks such as the main church, city hall, or another central point of air transport demand concentration. The measure is given by the shortest effective distance (in km) from the nearest road point (municipal, state, or federal) to the centroid of the potential site up to the CGD. In cases involving site searches for multiple cities and thus multiple CGDs, the longest distance to each CGD is adopted;
- Land Accessibility, ACE (lower is better): refers to the ease of connecting the potential site to the regional transport network. This network includes municipal, state, and federal roads near the potential site. It is determined by the shortest distance (in km) from the centroid of the potential site to the nearest road that connects to the CGD. When the site search involves multiple cities and thus multiple CGDs, the longest distance to each CGD is used;
- Availability of Public Services, DIP (lower is better): refers to the current availability of electric power services near the potential site. The considered network is medium or low voltage, excluding high-voltage lines if present. It is defined by the shortest distance (in km) from the centroid of the potential site to the nearest medium or low voltage electric network. In cases of site searches involving multiple cities and consequently multiple CGDs, the longest distance to each CGD is considered.

These six criteria are organized in the two-level hierarchy of Fig. 3, which separates concerns intrinsic to the airport from those intrinsic to the city. Table 1 summarizes, for each criterion, the metric used to quantify it, the nature of that metric, and its direction.



GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services.

**Figure 3.** Analytic hierarchy process-airport site selection methodology decision tree.

**Table 1.** Airport site selection methodology classification criteria: metric, nature of the measurement, and direction of merit.

| Criterion | Analysis metric                               | Nature                  | Merit            |
|-----------|-----------------------------------------------|-------------------------|------------------|
| GEO       | DCP soil penetration test analysis            | Proxy (CBR)             | Higher is better |
| TOP       | Earthmoving volume for cut and fill           | Proxy (m <sup>3</sup> ) | Lower is better  |
| RUI       | Number of properties within the 65 dB contour | Proxy (count)           | Lower is better  |
| DIS       | Distance to the demand-generating center      | Natural (km)            | Lower is better  |
| ACE       | Distance to the nearest connecting road       | Natural (km)            | Lower is better  |
| DIP       | Distance to the medium/low voltage network    | Proxy (km)              | Lower is better  |

GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services; DCP: dynamic cone penetrometer.

A note on versions is needed here, because the structure of this hierarchy changed after the case reported in the case study section was carried out. The study was conducted in 2018 and 2019 under the version of MESA then in force, which used the two-level tree of Fig. 3. The manual published in 2021 subsequently flattened that structure into a single level in which the six criteria are compared directly against one another (Brasil 2021). The criteria themselves, their metrics, and the normalization and aggregation procedures are identical in both versions; what changes is only how the comparisons are elicited and how the weights are composed. The practical difference is the number of judgments each expert must supply: the two-level tree requires eight pairwise comparisons, one at the first level, one between the two airport criteria, and six among the four city criteria, whereas the single-level tree requires 15.

This distinction matters for the consistency results reported later. In the two-level structure, the two first comparisons are  $2 \times 2$  and therefore consistent by construction, so redundancy exists only among the six judgments of the city branch and consistency can be assessed over those alone. The single-level structure of the current manual makes all 15 judgments mutually testable and would consequently detect incoherence that the two-level structure cannot see. The inconsistency rates we report should be read with that in mind: they are a lower bound on what a fully connected comparison set would have revealed.

Weights are obtained from the judgments in the standard AHP manner. It is considered a set of criteria  $C = [c_1, c_2, \dots, c_n]$  at a given level of the hierarchy. Each expert compares them in pairs, producing a judgment matrix  $A = [a_{ij}]$ , where  $a_{ij}$  expresses the importance of  $c_i$  relative to  $c_j$  on Saaty's fundamental scale from 1 (equal importance) to 9 (extreme importance), or its reciprocal when  $c_j$  dominates  $c_i$  (Saaty 1990). The weight vector  $w = (w_1, \dots, w_n)$  is the normalized principal eigenvector of  $A$ , that is, the solution (Eq. 1):

$$A w = \lambda_{\max} w \quad (1)$$

The existence with strictly positive components is guaranteed by the Perron-Frobenius theorem (Gomes *et al.* 2004). The coherence of each judgment matrix is assessed by the consistency ratio (Eq. 2):

$$CR = \frac{CI}{RI}, \quad CI = \frac{\lambda_{\max} - n}{n - 1} \quad (2)$$

Where:  $RI$ : the random index tabulated for random matrices of order  $n$ .

Values of  $CR$  exceeding 0.10 indicate potentially inconsistent judgments. In MESA, this threshold is not advisory: experts whose judgments exceed it are excluded from the aggregation, as described in stage 3. Note that for the two  $2 \times 2$  comparisons of this hierarchy (AER *versus* CID, and GEO *versus* TOP) the consistency ratio is 0 by construction, so only the  $4 \times 4$  comparison among the city criteria can be inconsistent.

### Stage 2: Metrics of the candidate sites

Objective metrics related to the established criteria are gathered for each candidate site. These metrics, termed *direct quantities*, are derived from geographic information systems or from fieldwork performed in the previous phase, and are obtained either directly from field measurements or indirectly through the interpretation of satellite imagery, with satisfactory accuracy levels.

Because the six criteria are measured in different units,  $m^3$ , km, counts, and CBR values, they cannot be combined as they stand. MESA therefore normalizes them into a dimensionless decision matrix before any weighting takes place. Let  $x_{ij}$  be the raw measurement of alternative  $a_i$  on criterion  $c_j$ . For benefit criteria, where higher is better, the normalized value is calculated by Eq. 3:

$$v_{ij} = \frac{x_{ij}}{\sum_{k=1}^m x_{kj}} \quad (3)$$

For cost criteria, where lower is better, the raw values are inverted before normalization (Eq. 4):

$$v_{ij} = \frac{1/x_{ij}}{\sum_{k=1}^m 1/x_{kj}} \quad (4)$$

So, in both cases a higher  $v_{ij}$  denotes better performance and each column sums to one. The resulting *normalized decision matrix* is calculated by Eq. 5:

$$V = \begin{bmatrix} v_{11} & v_{12} & \dots & v_{1n} \\ v_{21} & v_{22} & \dots & v_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ v_{m1} & v_{m2} & \dots & v_{mn} \end{bmatrix} \quad (5)$$

### Stage 3: Site ranking

The criteria weights obtained in stage 1 are combined with the normalized metrics from stage 2 to calculate the final score of each candidate site. In this process, each expert group performs its assessments independently. Inconsistent judgments are identified, and experts exhibiting a high level of inconsistency are excluded from the final analysis. Additionally, potential patterns of repetitive judgments that may indicate bias are assessed. The aim is to ensure the aggregated priority vector calculation is as unbiased as possible, not reflecting solely the opinion of one specific group but representing a consensus among all experts.

For a flat set of criteria, the score of alternative  $a_i$  is the inner product of the weight vector and the corresponding row of  $V$  (Eq. 6):

$$S_i = \sum_{j=1}^n w_j v_{ij} \quad (6)$$

The alternatives are ordered by decreasing  $S_i$ . In the two-level hierarchy of Fig. 3, Eq. 6 specializes to the global priority of alternative  $A_n$  (Eq. 7):

$$W_{A_n}^g = W^{aer} (W^{geo} v_{geo,A_n} + W^{top} v_{top,A_n}) + W^{cid} (W^{rui} v_{rui,A_n} + W^{dis} v_{dis,A_n} + W^{ace} v_{ace,A_n} + W^{dip} v_{dip,A_n}) \quad (7)$$

Where:  $W^{aer}$  and  $W^{cid}$ : the first-level weights;  $W_i$ : the weight of criterion  $i$  within its branch;  $v_{i,A}$ : the normalized measure of criterion  $i$  for alternative  $A_n$ .

The product of a first-level weight and a second-level weight, for instance  $W^{aer} W^{top}$ , is the *global weight* of the corresponding criterion; these global weights sum to one and are used in the Discussion section to examine what drives the ranking.

The result is an objective ranking that identifies the most favorable sites for airport implementation, considering all relevant criteria and their collectively determined relative importance. This application of AHP within MESA represents an important contribution toward increasing objectivity in the decision-making process, reducing subjectivity, and enabling transparent documentation of the rationale behind the final airport site selection.

## CASE STUDY: SOUTHWESTERN PARANÁ

This section applies MESA to the search for a regional airport site serving Francisco Beltrão and Pato Branco, in southwestern Paraná, Brazil. It follows the same phase structure as the Methods section, so that each step of the methodology can be read against its execution. The site prospecting carried out by the ITA team, accompanied by technicians from SAC and regional experts, took place from December 2018 to August 2019, including technical works conducted in the laboratory and in the field.

### Phase I: Requirements and search area

The southwestern region of Paraná comprises 43 municipalities, whose economy is articulated around agro-industrial production; intensive agriculture is the dominant land use, occupying some 40% of the territory, with soybean as the main crop. The region has a combined population of about 596 thousand inhabitants and an urbanization rate of 66%, and Pato Branco and Francisco Beltrão are its two sub-regional centers (IPARDES 2009). Both cities are served only by small aerodromes constrained by urban growth, which is what motivated the search for a single new site able to serve them jointly.

Initially, a search area was defined by intersecting two circles, each with a radius of 30 km, centered around the CGDs of the mentioned cities, adopting the respective main churches as reference points. This area covered territories in five municipalities of Paraná: Itapejara do Oeste, Bom Sucesso do Sul, Renascença, Vitorino, and Pato Branco, totaling approximately 550 km<sup>2</sup>.

### Phase II: Reduction of the search area

Restrictive layers were overlaid on the search area through geoprocessing. The layers considered included conservation and permanent preservation areas, the vicinity of existing aerodromes, urban perimeters, the landfill of Francisco Beltrão, perennial watercourses with a 30-m buffer on each bank, water bodies with a 100-m buffer, transmission and distribution lines, and municipal boundaries. What remained after these exclusions was the feasible land within which candidate sites could be positioned (ITA 2019b).

### Phase III: Identification of candidate sites

Ten potential sites with adequate geometry for the design aircraft were identified within the feasible area, labelled 1, 2, 2A, 2B, 2C, 3, 4, 5, 6, and 7 (Fig. 4). Five of them did not survive the exclusionary analysis of this phase. Sites 1, 5, 6, and 7 were ruled out because natural obstacles penetrate the obstacle limitation surfaces prescribed by Ordinance No. 957/GC3 (República Federativa do Brasil 2015). Site 2B was ruled out after a transmission line was identified in a position incompatible with the runway strip. The five surviving sites, 2, 2A, 2C, 3 and 4, are those carried forward to the field campaign and to the ranking reported below (ITA 2019b).

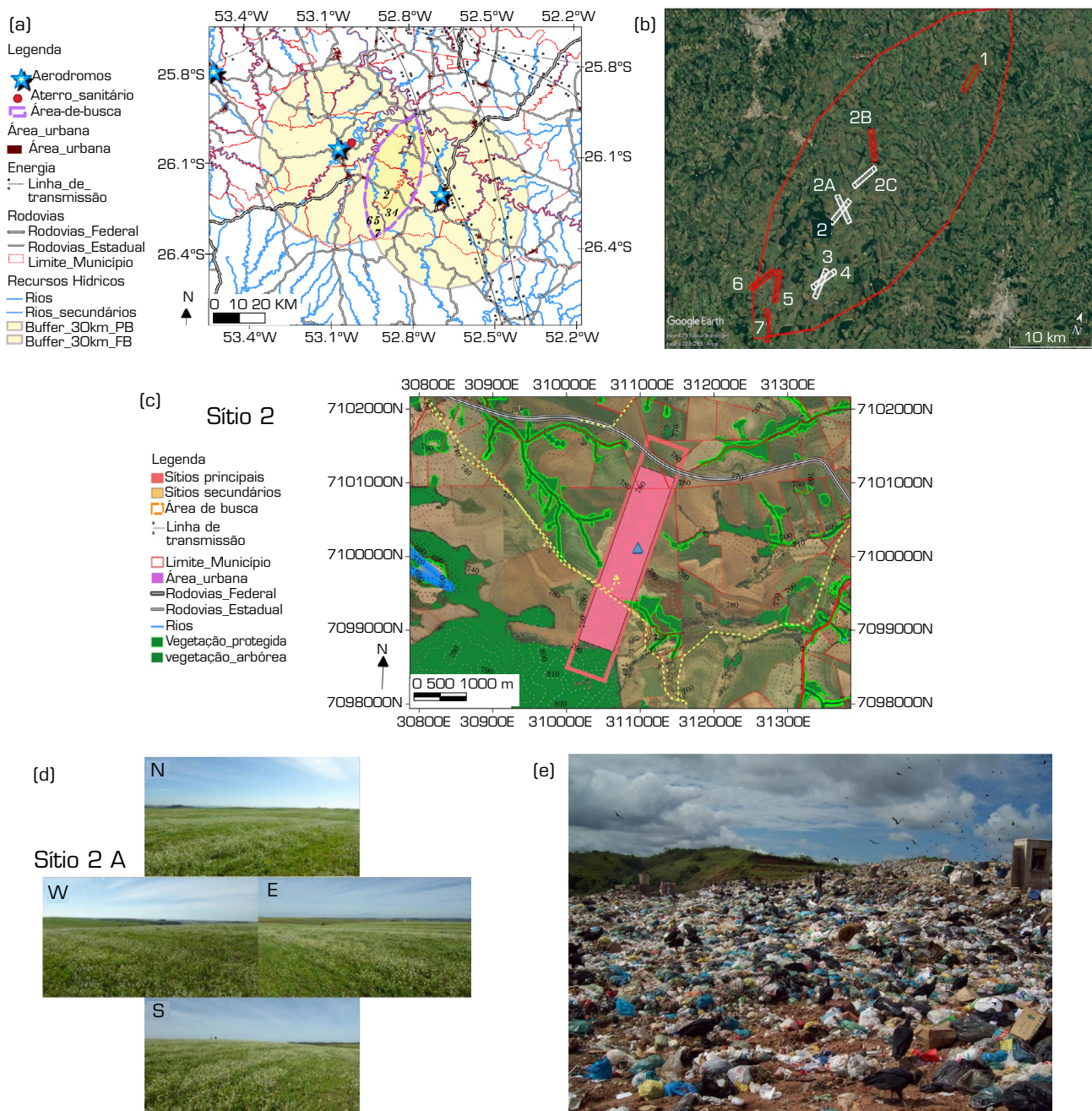
### Phase IV: Fieldwork

The field campaign took place from 24 to 27 of June 2019 and involved the ITA team together with representatives of SAC, the Paraná State Secretariat of Transport and Logistics, the local municipalities, and AMSOP, the association of municipalities of southwestern Paraná. The group was split in two teams: one visited every candidate site for reconnaissance and access planning, while the other collected soil data and verified the topographic model. The sites were surveyed on foot, with data collected on soil type, altimetry and land cover, and the landfill of Francisco Beltrão was also visited so that its influence on the surrounding sites could be assessed (ITA 2019b). Figure 4 documents this sequence.

### Phase V: Prioritization of the candidate sites

#### *Expert groups and consistency*

Three distinct groups of experts were selected: federal representatives from SAC, academics from ITA, and local authorities from municipalities in the region and the Secretariat of Infrastructure and Logistics of the State of Paraná, hereafter the SUDO group. In total, 33 experts took part, 11 from SAC, nine from ITA, and 13 from SUDO. The composition of each group is relevant to the interpretation of the results in the Discussion section: the SAC participants were drawn mostly from the secretariat's cadre of infrastructure analysts; the ITA participants were faculty and researchers in air transport, geoprocessing and environmental



**Figure 4.** The case study through the airport site selection methodology (MESA) phases. (a) The 550-km<sup>2</sup> search area delimited in phase I by the intersection of two 30-km circles centered on the demand-generating centers of Pato Branco and Francisco Beltrão, PR, Brazil. (b) The 10 sites identified in phase III over the feasible land; sites drawn in red were subsequently ruled out by the obstacle and transmission line constraints described in the subsection “Phase IV: Fieldwork”, and those in white went to the field. (c) Detailed cartography of site 2A, showing runway orientation and surroundings. (d) Phase IV field inspection of site 2A. (e) Francisco Beltrão’s landfill, one of the restrictive elements mapped in phase II, which constrains the placement of sites in its vicinity because of the associated bird strike hazard

engineering; and the SUDO participants, designated by the Paraná State Secretariat of Transport and Logistics and by the local city halls with the participation of AMSOP, the association of municipalities of southwestern Paraná, mostly hold planning positions in their respective municipal governments (ITA 2019b).

The elicitation followed a common protocol for all three groups. Before making any judgment, every participant received the same briefing material, which defined each classification criterion, stated the metric by which it would be measured, presented the case to be decided, and introduced Saaty's fundamental scale through a worked example unrelated to airports. The decision hierarchy of Fig. 3 was fixed *a priori* by the ITA team and was not open to negotiation by the panel, so that all groups judged the same structure. Judgments were then entered individually through a dedicated web application, which recorded the pairwise comparisons and computed the priority vectors and consistency ratios; a second application performed the IAP aggregation, and a third produced the site ranking (ITA 2019b). Participants did not show their consistency ratio during the session and had no opportunity to revise a matrix found to be inconsistent, a limitation we return to in the Discussion section.

Table 2 presents the priorities estimated by the 11 SAC experts. Rows marked with a dagger identify the experts whose judgments were inconsistent, that is, whose consistency ratio for the four city criteria,  $CR_3$ , exceeded 10%. According to MESA methodology guidelines, judgments from experts who demonstrated inconsistency were excluded from the decision-making process for the southwestern Paraná case. As noted in the subsection "Phase V: Prioritization of candidate sites," the consistency ratios of the two  $2 \times 2$  comparisons are identically 0 and are therefore omitted from Table 2 and from the corresponding tables of the ITA and SUDO groups.

**Table 2.** Judgments from Civil Aviation Secretariat experts and consistency status.

| Expert         | Level 1 |      | Airport |      | City |      |      |      | CR3  | Status |
|----------------|---------|------|---------|------|------|------|------|------|------|--------|
|                | AER     | CID  | GEO     | TOP  | RUI  | DIS  | ACE  | DIP  |      |        |
| 1              | 0.67    | 0.33 | 0.20    | 0.80 | 0.53 | 0.08 | 0.17 | 0.22 | 0.02 | CON    |
| 2 <sup>†</sup> | 0.50    | 0.50 | 0.50    | 0.50 | 0.17 | 0.48 | 0.31 | 0.04 | 0.52 | INC    |
| 3 <sup>†</sup> | 0.50    | 0.50 | 0.33    | 0.67 | 0.12 | 0.24 | 0.36 | 0.29 | 0.27 | INC    |
| 4              | 0.25    | 0.75 | 0.75    | 0.25 | 0.57 | 0.07 | 0.19 | 0.17 | 0.04 | CON    |
| 5              | 0.25    | 0.75 | 0.67    | 0.33 | 0.49 | 0.14 | 0.17 | 0.20 | 0.07 | CON    |
| 6 <sup>†</sup> | 0.25    | 0.75 | 0.50    | 0.50 | 0.12 | 0.21 | 0.60 | 0.07 | 0.12 | INC    |
| 7 <sup>†</sup> | 0.88    | 0.12 | 0.13    | 0.88 | 0.05 | 0.56 | 0.27 | 0.12 | 0.29 | INC    |
| 8              | 0.33    | 0.67 | 0.33    | 0.67 | 0.23 | 0.30 | 0.36 | 0.11 | 0.02 | CON    |
| 9              | 0.67    | 0.33 | 0.33    | 0.67 | 0.07 | 0.38 | 0.41 | 0.14 | 0.03 | CON    |
| 10             | 0.75    | 0.25 | 0.67    | 0.33 | 0.55 | 0.21 | 0.14 | 0.09 | 0.02 | CON    |
| 11             | 0.33    | 0.67 | 0.17    | 0.83 | 0.11 | 0.25 | 0.25 | 0.39 | 0.06 | CON    |

<sup>†</sup> $CR_3 > 0.10$ ; judgments excluded from the aggregation; AER: airport criteria; CID: city criteria; CON: consistent; INC: inconsistent; GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services.

Subsequently, Table 3 presents the IAP for the SAC group, considering only the subset of experts whose judgments were consistent. The table also includes the sample standard deviation of the IAP values.

**Table 3.** Weights and standard deviations of the criteria for the Civil Aviation Secretariat group (consistent experts).

| Criterion | Weight (IAP) | Standard deviation |
|-----------|--------------|--------------------|
| AER       | 0.46         | 0.22               |
| CID       | 0.54         | 0.22               |
| GEO       | 0.45         | 0.24               |
| TOP       | 0.55         | 0.24               |
| RUI       | 0.36         | 0.22               |
| DIS       | 0.21         | 0.11               |
| ACE       | 0.24         | 0.11               |
| DIP       | 0.19         | 0.10               |

AER: airport criteria; CID: city criteria; GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services; IAP: individual aggregation of priorities.

Table 4 displays the priorities estimated by the nine experts from the ITA group. Similarly, evaluations from experts whose judgments were inconsistent were discarded from the process.

**Table 4.** Judgments from Instituto Tecnológico de Aeronáutica experts and their consistency status.

| Expert         | Level 1 |      | Airport |      | City |      |      |      | CR3  | Status |
|----------------|---------|------|---------|------|------|------|------|------|------|--------|
|                | AER     | CID  | GEO     | TOP  | RUI  | DIS  | ACE  | DIP  |      |        |
| 1              | 0.83    | 0.17 | 0.13    | 0.88 | 0.10 | 0.40 | 0.40 | 0.10 | 0.00 | CON    |
| 2              | 0.50    | 0.50 | 0.75    | 0.25 | 0.11 | 0.41 | 0.41 | 0.08 | 0.04 | CON    |
| 3 <sup>†</sup> | 0.83    | 0.17 | 0.25    | 0.75 | 0.31 | 0.53 | 0.13 | 0.03 | 0.19 | INC    |
| 4              | 0.83    | 0.17 | 0.75    | 0.25 | 0.06 | 0.41 | 0.41 | 0.11 | 0.06 | CON    |
| 5 <sup>†</sup> | 0.86    | 0.14 | 0.20    | 0.80 | 0.54 | 0.12 | 0.28 | 0.06 | 0.19 | INC    |
| 6              | 0.20    | 0.80 | 0.33    | 0.67 | 0.51 | 0.20 | 0.20 | 0.09 | 0.03 | CON    |
| 7              | 0.17    | 0.83 | 0.50    | 0.50 | 0.06 | 0.48 | 0.34 | 0.11 | 0.08 | CON    |
| 8 <sup>†</sup> | 0.83    | 0.17 | 0.13    | 0.88 | 0.43 | 0.22 | 0.21 | 0.13 | 0.26 | INC    |
| 9              | 0.14    | 0.86 | 0.13    | 0.88 | 0.59 | 0.16 | 0.17 | 0.07 | 0.05 | CON    |

<sup>†</sup>CR<sub>3</sub> > 0.10; judgments excluded from the aggregation; AER: airport criteria; CID: city criteria; GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services; CON: consistent; INC: inconsistent.

The priorities determined by the ITA group for the airport site selection criteria, considering only the consistent experts, are presented in Table 5.

**Table 5.** Weights and standard deviations of criteria for the Instituto Tecnológico de Aeronáutica group (consistent experts).

| Criterion | Weight (IAP) | Standard deviation |
|-----------|--------------|--------------------|
| AER       | 0.45         | 0.33               |
| CID       | 0.55         | 0.33               |
| GEO       | 0.43         | 0.28               |
| TOP       | 0.57         | 0.28               |
| RUI       | 0.24         | 0.24               |
| DIS       | 0.34         | 0.13               |
| ACE       | 0.32         | 0.11               |
| DIP       | 0.09         | 0.02               |

AER: airport criteria; CID: city criteria; GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services; IAP: individual aggregation of priorities.

Table 6 details the results of the priorities estimated by the 13 experts comprising the SUDO group (specialists nominated by municipal and state authorities). In this group, only five out of the 13 experts provided consistent evaluations.

**Table 6.** Judgments from Secretariat of Infrastructure and Logistics of the State of Paraná experts and their consistency status.

| Expert          | Level 1 |      | Airport |      | City |      |      |      | CR3  | Status |
|-----------------|---------|------|---------|------|------|------|------|------|------|--------|
|                 | AER     | CID  | GEO     | TOP  | RUI  | DIS  | ACE  | DIP  |      |        |
| 1               | 0.90    | 0.10 | 0.10    | 0.90 | 0.06 | 0.06 | 0.57 | 0.31 | 0.05 | CON    |
| 2               | 0.90    | 0.10 | 0.10    | 0.90 | 0.06 | 0.07 | 0.61 | 0.26 | 0.08 | CON    |
| 3 <sup>†</sup>  | 0.90    | 0.10 | 0.17    | 0.83 | 0.06 | 0.13 | 0.32 | 0.49 | 0.18 | INC    |
| 4 <sup>†</sup>  | 0.90    | 0.10 | 0.10    | 0.90 | 0.31 | 0.08 | 0.32 | 0.29 | 0.26 | INC    |
| 5               | 0.90    | 0.10 | 0.10    | 0.90 | 0.06 | 0.07 | 0.56 | 0.31 | 0.06 | CON    |
| 6               | 0.33    | 0.67 | 0.33    | 0.67 | 0.36 | 0.08 | 0.38 | 0.18 | 0.08 | CON    |
| 7 <sup>†</sup>  | 0.88    | 0.12 | 0.17    | 0.83 | 0.08 | 0.07 | 0.59 | 0.25 | 0.18 | INC    |
| 8 <sup>†</sup>  | 0.90    | 0.10 | 0.89    | 0.11 | 0.04 | 0.08 | 0.60 | 0.28 | 0.17 | INC    |
| 9 <sup>†</sup>  | 0.67    | 0.33 | 0.75    | 0.25 | 0.27 | 0.08 | 0.49 | 0.17 | 0.12 | INC    |
| 10 <sup>†</sup> | 0.88    | 0.12 | 0.11    | 0.89 | 0.10 | 0.07 | 0.56 | 0.28 | 0.18 | INC    |
| 11              | 0.90    | 0.10 | 0.10    | 0.90 | 0.06 | 0.07 | 0.61 | 0.26 | 0.08 | CON    |
| 12 <sup>†</sup> | 0.89    | 0.11 | 0.20    | 0.80 | 0.06 | 0.14 | 0.37 | 0.42 | 0.13 | INC    |
| 13 <sup>†</sup> | 0.90    | 0.10 | 0.89    | 0.11 | 0.04 | 0.10 | 0.61 | 0.25 | 0.15 | INC    |

<sup>†</sup>CR<sub>3</sub> > 0.10; judgments excluded from the aggregation; AER: airport criteria; CID: city criteria; GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services; CON: consistent; INC: inconsistent.



Table 7 presents the IAP for the SUDO group over its five consistent experts.

**Table 7.** Weights and standard deviations of criteria for the Secretariat of Infrastructure and Logistics of the State of Paraná group (consistent experts).

| Criterion | Weight (IAP) | Standard deviation |
|-----------|--------------|--------------------|
| AER       | 0.79         | 0.25               |
| CID       | 0.21         | 0.25               |
| GEO       | 0.15         | 0.10               |
| TOP       | 0.85         | 0.10               |
| RUI       | 0.12         | 0.13               |
| DIS       | 0.07         | 0.01               |
| ACE       | 0.55         | 0.10               |
| DIP       | 0.26         | 0.05               |

AER: airport criteria; CID: city criteria; GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services; IAP: individual aggregation of priorities.

Finally, Table 8 presents the priorities of the general group, denoted ALL. These weights were obtained by applying the IAP over the pooled set of all consistent experts from the three groups, seven from SAC, six from ITA, and five from SUDO, 18 in total. That is, the general vector is the arithmetic mean of the 18 individual priority vectors, and no additional pairwise comparison matrix was elicited for it. This procedure is equivalent to a weighted average of the three group vectors of Tables 3, 5 and 7, with weights proportional to the number of consistent experts in each group.

**Table 8.** General group's IAP and sample standard deviation for the set of consistent experts.

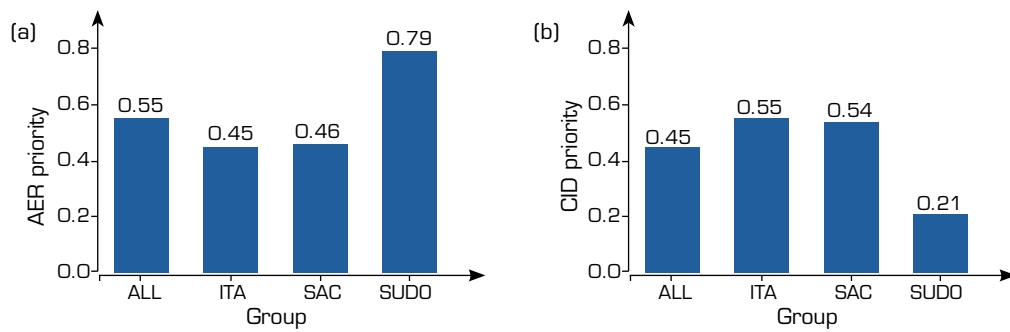
| Criterion | Weight (IAP) | Standard deviation |
|-----------|--------------|--------------------|
| AER       | 0.55         | 0.29               |
| CID       | 0.45         | 0.29               |
| GEO       | 0.36         | 0.26               |
| TOP       | 0.64         | 0.26               |
| RUI       | 0.25         | 0.22               |
| DIS       | 0.21         | 0.15               |
| ACE       | 0.35         | 0.16               |
| DIP       | 0.18         | 0.09               |

AER: airport criteria; CID: city criteria; GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services; IAP: individual aggregation of priorities.

Figure 5 provides an overview of the estimated priorities by group and the overall IAP result. All panels share the same vertical scale so that the magnitude of the differences can be compared directly across criteria. Figures 5a and 5b show the estimated priorities for the criteria AER and CID, at the first level of the hierarchy, representing aspects related respectively to the airport and the city. Analysis of these figures suggests convergence in the priority estimations provided by the ITA and SAC groups for these criteria.

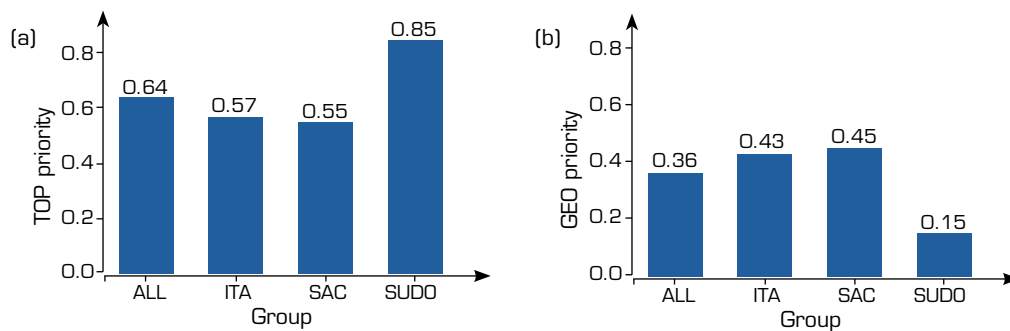
Similarly, the GEO and TOP criteria also showed judgment convergence among experts from the ITA and SAC groups, as observed in Fig. 6.

On the other hand, for the criteria RUI, DIS, ACE, and DIP, the groups did not demonstrate clear convergence of opinions or perceptions, as shown in Fig. 7.



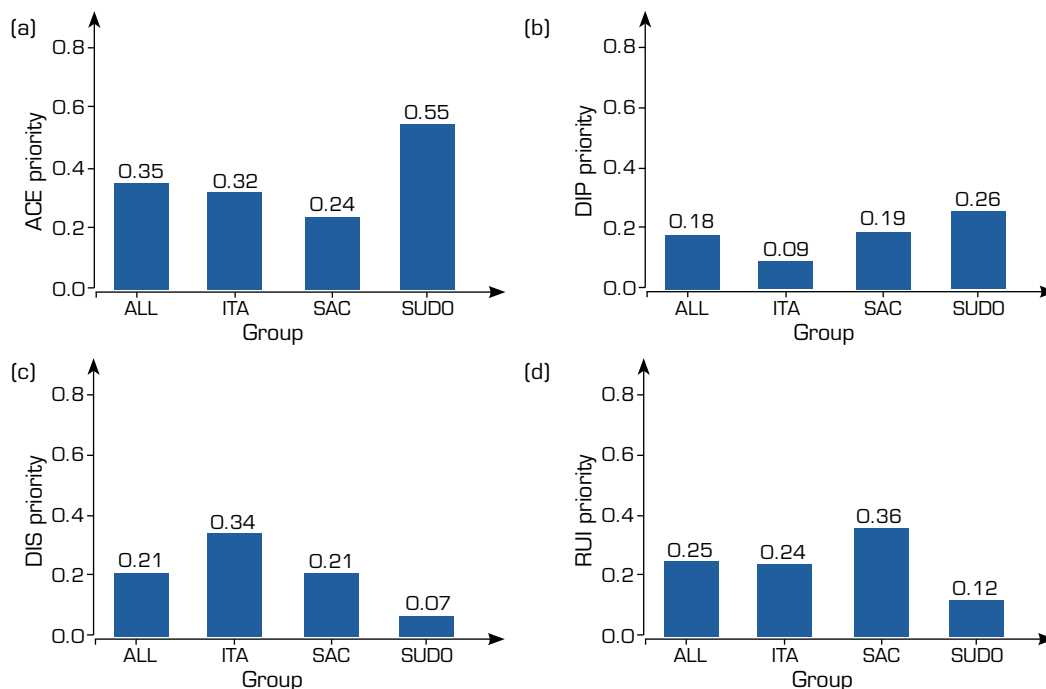
ITA: Instituto Tecnológico de Aeronáutica; SAC: Civil Aviation Secretariat; SUDO: Secretariat of Infrastructure and Logistics of the State of Paraná.

**Figure 5.** Priorities for the first-level criteria of the hierarchy: (a) airport criterion (AER); (b) city criterion (CID).



ITA: Instituto Tecnológico de Aeronáutica; SAC: Civil Aviation Secretariat; SUDO: Secretariat of Infrastructure and Logistics of the State of Paraná.

**Figure 6.** Priorities for the airport-related criteria: (a) topography criterion (TOP); (b) Geology criterion (GEO).



ITA: Instituto Tecnológico de Aeronáutica; SAC: Civil Aviation Secretariat; SUDO: Secretariat of Infrastructure and Logistics of the State of Paraná.

**Figure 7.** Priorities for the city-related criteria, where the groups diverge: (a) accessibility criterion (ACE); (b) availability criterion (DIP); (c) distance criterion (DIS); (d) noise criterion (RUI).

## Statistical analysis of priorities among the expert groups

Because the group samples were small and normality could not be assumed, group-specific priority distributions were compared with two-sided Wilcoxon–Mann–Whitney’s tests. For each criterion and pair of groups, the null hypothesis was that the two distributions had the same location (Eq. 8):

$$\begin{aligned}
 H_0 : md_{ITA} &= md_{SAC} \\
 H_1 : md_{ITA} &\neq md_{SAC} \\
 \\
 H_0 : md_{ITA} &= md_{SUDO} \\
 H_1 : md_{ITA} &\neq md_{SUDO} \\
 \\
 H_0 : md_{SAC} &= md_{SUDO} \\
 H_1 : md_{SAC} &\neq md_{SUDO}
 \end{aligned} \tag{8}$$

Where: *md*: the location parameter, commonly interpreted as a median shift when the two distributions have similar shapes.

The tests are exploratory: the reported *p*-values are unadjusted across the 24 criterion-wise comparisons. Accordingly,  $p > 0.05$  is interpreted as insufficient evidence of a difference, not as evidence that the groups are equivalent. Tables 9–11 report the results.

At the unadjusted 5% level, ITA and SAC differed only for DIP. ITA and SUDO differed for all criteria except RUI, whereas SAC and SUDO differed for all criteria except DIP. These exploratory results describe the present samples and do not establish equivalence where a test was nonsignificant. The subsection “Why the groups judge differently,” in the Discussion section, examines the observed group profiles.

**Table 9.** Wilcoxon-Mann-Whitney’s test, Instituto Tecnológico de Aeronáutica *versus* Civil Aviation Secretariat.

| Criterion | W  | <i>p</i> -value | Result                       |
|-----------|----|-----------------|------------------------------|
| AER       | 18 | 0.7195          | not significant (unadjusted) |
| CID       | 24 | 0.7195          | not significant (unadjusted) |
| GEO       | 20 | 0.9423          | not significant (unadjusted) |
| TOP       | 22 | 0.9423          | not significant (unadjusted) |
| RUI       | 13 | 0.2949          | not significant (unadjusted) |
| DIS       | 34 | 0.0734          | not significant (unadjusted) |
| ACE       | 29 | 0.2949          | not significant (unadjusted) |
| DIP       | 5  | 0.0221          | $p < 0.05$ (unadjusted)      |

AER: airport criteria; CID: city criteria; GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services.

**Table 10.** Wilcoxon-Mann-Whitney’s test, Instituto Tecnológico de Aeronáutica *versus* Secretariat of Infrastructure and Logistics of the State of Paraná.

| Criterion | W    | <i>p</i> -value | Result                       |
|-----------|------|-----------------|------------------------------|
| AER       | 3.0  | 0.0312          | $p < 0.05$ (unadjusted)      |
| CID       | 27.0 | 0.0312          | $p < 0.05$ (unadjusted)      |
| GEO       | 27.5 | 0.0239          | $p < 0.05$ (unadjusted)      |
| TOP       | 2.5  | 0.0239          | $p < 0.05$ (unadjusted)      |
| RUI       | 22.0 | 0.2343          | not significant (unadjusted) |
| DIS       | 30.0 | 0.0080          | $p < 0.05$ (unadjusted)      |
| ACE       | 3.0  | 0.0353          | $p < 0.05$ (unadjusted)      |
| DIP       | 0.0  | 0.0080          | $p < 0.05$ (unadjusted)      |

AER: airport criteria; CID: city criteria; GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services.

**Table 11.** Wilcoxon-Mann-Whitney's test, Civil Aviation Secretariat *versus* Secretariat of Infrastructure and Logistics of the State of Paraná.

| Criterion | W  | p-value | Result                       |
|-----------|----|---------|------------------------------|
| AER       | 4  | 0.0298  | $p < 0.05$ (unadjusted)      |
| CID       | 31 | 0.0298  | $p < 0.05$ (unadjusted)      |
| GEO       | 32 | 0.0195  | $p < 0.05$ (unadjusted)      |
| TOP       | 3  | 0.0195  | $p < 0.05$ (unadjusted)      |
| RUI       | 32 | 0.0228  | $p < 0.05$ (unadjusted)      |
| DIS       | 33 | 0.0147  | $p < 0.05$ (unadjusted)      |
| ACE       | 1  | 0.0092  | $p < 0.05$ (unadjusted)      |
| DIP       | 7  | 0.1038  | not significant (unadjusted) |

AER: airport criteria; CID: city criteria; GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services.

## METRICS OF THE CLASSIFICATION CRITERIA

MESA establishes that defining the metrics for classification criteria does not require input from the expert group, as these criteria can be measured directly during inspections of candidate sites or indirectly through interpretation of georeferenced maps and satellite imagery.

Following the completion of field and office work stages, adjusted measures for the classification criteria were structured as presented in Table 12, with units of the criteria specified as follows: GEO (natural CBR value), TOP (volume in m<sup>3</sup>), RUI (number of buildings), DIS (distance in km), ACE (distance in km), and DIP (distance in km).

**Table 12.** Measures of classification criteria for candidate sites.

| Site | GEO  | TOP       | RUI | DIS  | ACE | DIP |
|------|------|-----------|-----|------|-----|-----|
| 2    | 11.0 | 3,879,616 | 1   | 22.1 | 1.3 | 0.4 |
| 2A   | 11.0 | 6,387,976 | 1   | 23.1 | 1.0 | 0.9 |
| 2C   | 15.6 | 3,985,154 | 1   | 22.6 | 3.0 | 0.3 |
| 3    | 16.3 | 6,006,847 | 1   | 27.5 | 7.1 | 0.3 |
| 4    | 16.0 | 7,994,669 | 1   | 27.4 | 7.0 | 0.3 |

GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services.

In the subsequent analytical step, the measures of the criteria presented in Table 12 were normalized by Eqs. 3 and 4, GEO being the only benefit criterion and the remaining five cost criteria. The resulting normalized values are shown in Table 13.

**Table 13.** Normalized measures of classification criteria per site.

| Site | GEO  | TOP  | RUI  | DIS  | ACE  | DIP  |
|------|------|------|------|------|------|------|
| 2    | 0.16 | 0.27 | 0.20 | 0.22 | 0.32 | 0.18 |
| 2A   | 0.16 | 0.16 | 0.20 | 0.21 | 0.42 | 0.08 |
| 2C   | 0.22 | 0.26 | 0.20 | 0.22 | 0.14 | 0.24 |
| 3    | 0.23 | 0.17 | 0.20 | 0.18 | 0.06 | 0.24 |
| 4    | 0.23 | 0.13 | 0.20 | 0.18 | 0.06 | 0.24 |

GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services.

## Site ranking

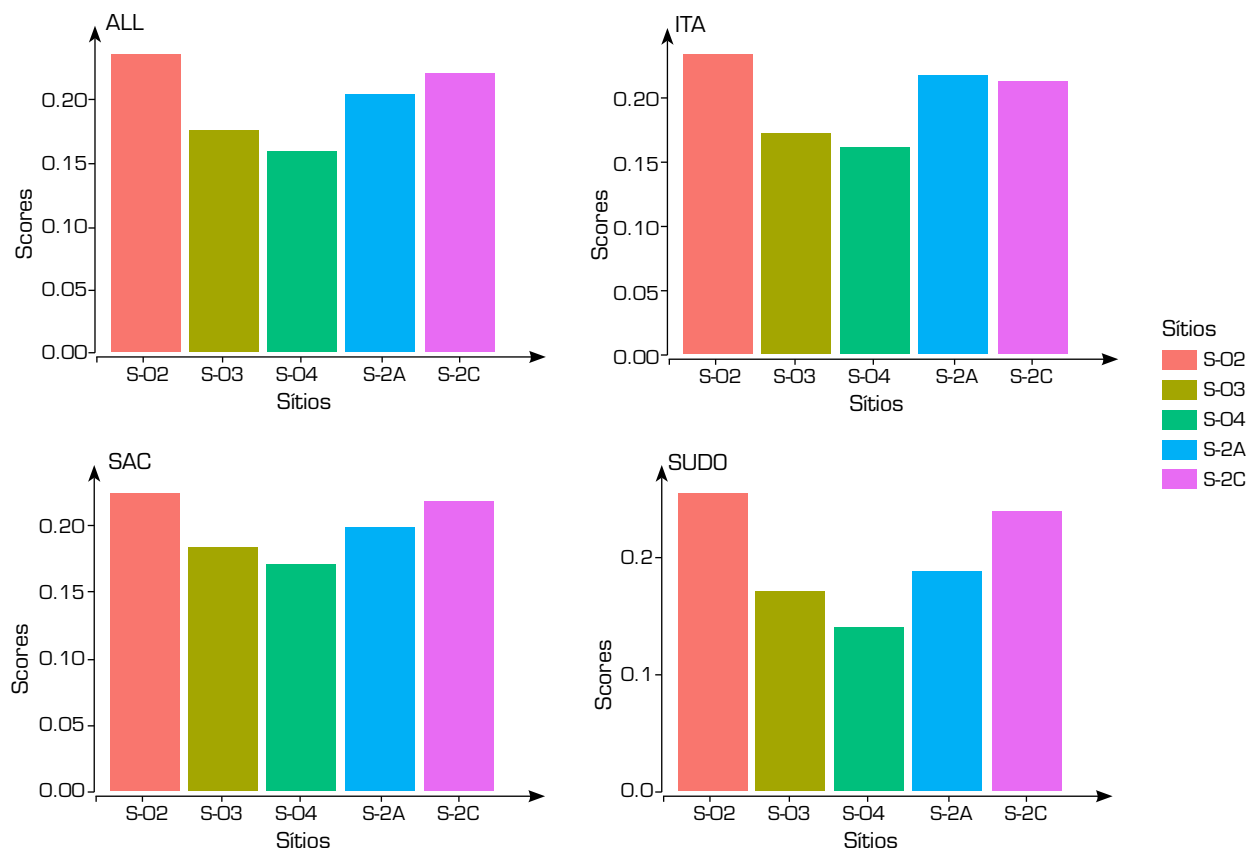
Finally, the global priority of each alternative was computed with Eq. 7. Specific weight sets for each expert group were used in separate analyses: the weights from Table 3 for the SAC group, Table 5 for ITA, and Table 7 for SUDO. For the consolidated global priority (ALL), the weights of the general group, presented in Table 8, were applied. In each analysis the weights were combined with the normalized measures of Table 13. The final ranking results are presented in Table 14.

**Table 14.** Final ranking results, expressed as global priorities  $W^g$ .

| Site | SAC    | ITA    | SUDO   | ALL    |
|------|--------|--------|--------|--------|
| 2    | 0.2254 | 0.2343 | 0.2553 | 0.2363 |
| 2A   | 0.1993 | 0.2176 | 0.1897 | 0.2053 |
| 2C   | 0.2193 | 0.2147 | 0.2402 | 0.2219 |
| 3    | 0.1839 | 0.1725 | 0.1721 | 0.1762 |
| 4    | 0.1721 | 0.1610 | 0.1427 | 0.1603 |

SAC: Civil Aviation Secretariat; ITA: Instituto Tecnológico de Aeronáutica; SUDO: Secretariat of Infrastructure and Logistics of the State of Paraná; ALL: aggregated group.

To visually reinforce these findings, Fig. 8 presents the performance of each candidate site according to the individual evaluations from the SAC, ITA, and SUDO groups, as well as the aggregated group (ALL).



SAC: Civil Aviation Secretariat; ITA: Instituto Tecnológico de Aeronáutica; SUDO: Secretariat of Infrastructure and Logistics of the State of Paraná; ALL: aggregated group.

**Figure 8.** Site ranking by decision-making group: ALL, ITA, SAC, and SUDO.

Sites 2, 2C, and 2A achieved the highest scores, with 0.2363, 0.2219, and 0.2053, respectively, for the general group (ALL). These three alternatives consistently ranked as the most favorable across all expert groups. Based on the application of MESA, the ITA team recommends that the new airport site for the southwest Paraná region be selected from among alternatives 2, 2C, and 2A.

## DISCUSSION

### What drives the ranking

Table 14 is stable in an interesting way: the first three positions are occupied by the same three sites under all four weighting schemes, and only the order of the second and third places changes, with 2A ahead of 2C for ITA and behind it for SAC, SUDO, and ALL. The recommendation therefore does not depend on which group's priorities are adopted, which is a useful property in a decision that will be scrutinized by those groups. The reason for that stability becomes clear when the hierarchy is collapsed into global weights, that is, when each second-level weight is multiplied by the first-level weight of its branch. Table 15 shows the result. One criterion dominates in every group: earthmoving volume, whose global weight ranges from 0.25 for SAC to 0.67 for SUDO. Site 2 has the lowest earthmoving volume of the five alternatives, 3.88 million m<sup>3</sup> against 7.99 million m<sup>3</sup> for the worst placed site, and it wins under every weighting for that reason. Site 2C, whose volume is only 3% higher than that of site 2, follows closely and additionally leads on geology. Site 2A, in contrast, has the best land accessibility of the set, 1 km from the nearest connecting road, but pays for it with an earthmoving volume 65% larger than that of site 2. That trade-off is what moves it between second and third place: the ITA group is the only one that weights accessibility and distance highly enough relative to topography for 2A to overtake 2C.

**Table 15.** Global weights of the classification criteria per group, obtained as the product of the first- and second-level weights of Tables 3 to 8. Values may not sum to 1 because of rounding.

| Criterion | SAC  | ITA  | SUDO | ALL  |
|-----------|------|------|------|------|
| GEO       | 0.21 | 0.19 | 0.12 | 0.20 |
| TOP       | 0.25 | 0.26 | 0.67 | 0.35 |
| RUI       | 0.19 | 0.13 | 0.03 | 0.11 |
| DIS       | 0.11 | 0.19 | 0.01 | 0.09 |
| ACE       | 0.13 | 0.18 | 0.12 | 0.16 |
| DIP       | 0.10 | 0.05 | 0.05 | 0.08 |

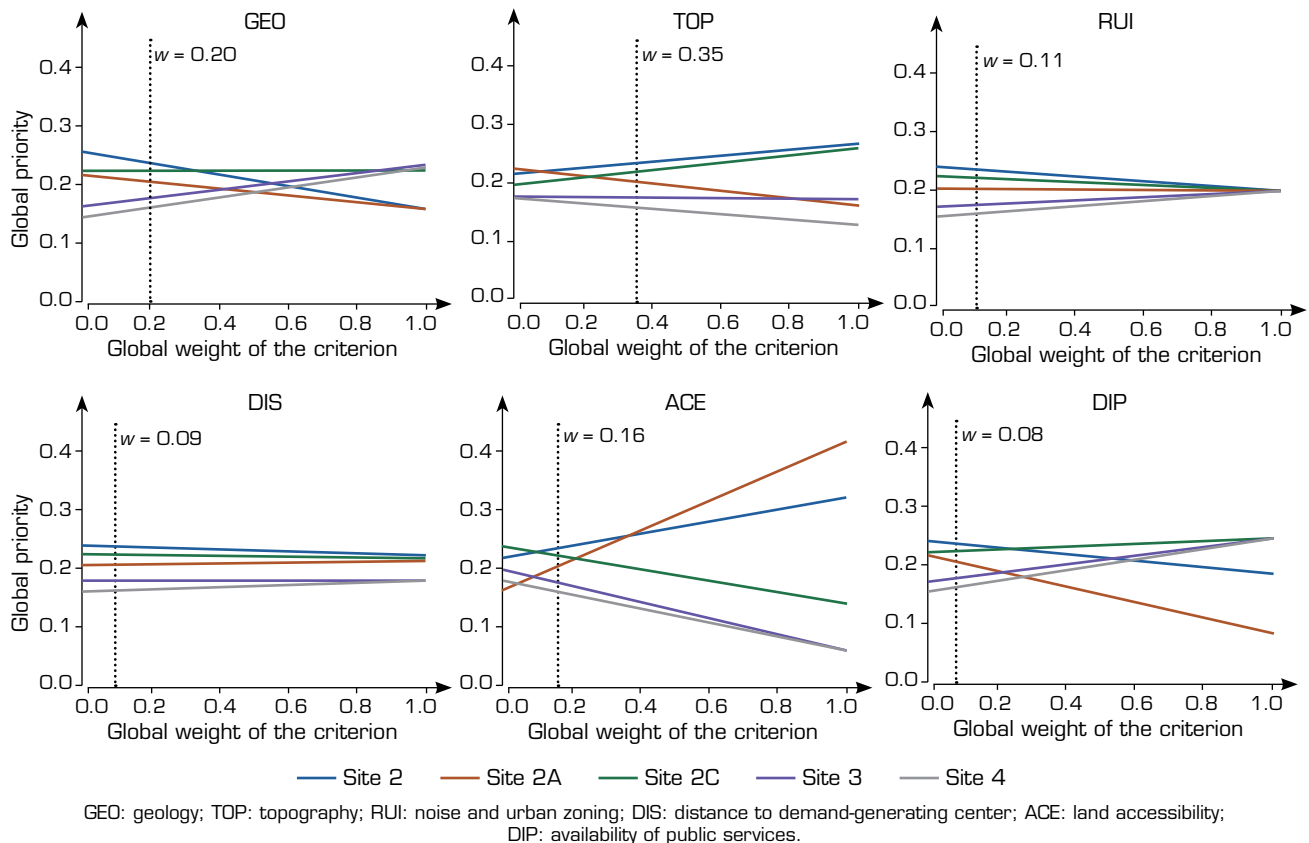
SAC: Civil Aviation Secretariat; ITA: Instituto Tecnológico de Aeronáutica; SUDO: Secretariat of Infrastructure and Logistics of the State of Paraná; ALL: aggregated group; GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services.

Two consequences deserve to be recorded. First, when a single criterion carries a third or more of the global weight, the ranking is effectively a ranking on that criterion, moderated by the others. Planners using MESA should therefore examine the global weights, and not only the level-by-level weights that the pairwise comparisons produce, since a criterion that looks moderately important within its branch can dominate the outcome once the branch weight is applied. Second, the noise criterion had no discriminating power at all in this case: every one of the five sites has one property inside the 65 dB contour, so RUI takes the same normalized value of 0.20 for all alternatives and contributes an identical amount to every score, regardless of the weight assigned to it. The 19% global weight that SAC assigned to noise had no effect whatsoever on the outcome. This is a property of the case, not of the methodology, and it is a direct consequence of the previous phases having already excluded urbanized land, but it illustrates that a criterion's weight and its influence are different things. Geology behaves in a milder version of the same way: the geotechnical survey found a homogeneous soil across the whole search area, a clayey purple latosol derived from basalt, resistant in its natural state, so the CBR values of the five sites span only 11 to 16.3, and GEO separates the alternatives far less than its 20% global weight would suggest (ITA 2019b).



## How much the weights would have to change

The previous subsection shows that one criterion dominates the arithmetic. The natural question is then how far the elicited weights would have to move before the recommendation itself changed. We answer it with a one-at-a-time sensitivity analysis on the global weights of the general group. The weight of one criterion is varied from 0 to 1 while the remaining five keep their relative proportions, so that they always sum to one. Under this perturbation, each site's global priority is a linear function of the varied weight, running from its value under the elicited weights to its normalized score on that criterion alone when the weight reaches 1. Figure 9 shows the six resulting families of lines, and Table 16 reports the intervals within which the conclusions hold.



**Figure 9.** Sensitivity of the global priorities to the weight of each criterion, general group (ALL). In each panel, the global weight of the criterion varies from 0 to 1 with the remaining weights rescaled proportionally. The dotted vertical line marks the weight actually elicited.

**Table 16.** Ranges of the global weight of each criterion within which the leading site and the recommended short list are preserved, general group (ALL).

| Criterion | Elicited weight | Site 2 remains first for | Short list [2, 2C, 2A] holds for |
|-----------|-----------------|--------------------------|----------------------------------|
| GEO       | 0.20            | $w < 0.34$               | $w < 0.42$                       |
| TOP       | 0.35            | $w > 0.08$               | $w < 0.83$                       |
| RUI       | 0.11            | any $w$                  | any $w$                          |
| DIS       | 0.09            | any $w$                  | any $w$                          |
| ACE       | 0.16            | $0.09 < w < 0.36$        | $w > 0.09$                       |
| DIP       | 0.08            | $w < 0.22$               | $w < 0.22$                       |

GEO: geology; TOP: topography; RUI: noise and urban zoning; DIS: distance to demand-generating center; ACE: land accessibility; DIP: availability of public services.

Three things follow. First, the short list of three sites that the ITA team recommended is robust: no single global weight can be reduced by up to 45% or increased by up to 109% of its elicited value without the set [2, 2C, 2A] remaining the three best alternatives, and for two criteria, noise and distance, no perturbation whatsoever changes it. The binding constraint is land accessibility on the downside, whose weight would have to fall from 0.16 to below 0.09 before site 3 or site 4 could enter the short list, and geology on the upside, whose weight would have to more than double.

Second, which of the three leads is a good deal less robust than the set itself. Site 2 loses the first position if geology is weighted above 0.34, if availability of public services is weighted above 0.22, or if land accessibility moves outside the narrow band between 0.09 and 0.36. This is consistent with the closeness of the scores in Table 14, in which site 2 and site 2C differ by only 0.014, and it is the quantitative justification for MESA delivering an ordered short list rather than a single winner: the evidence supports the statement that these three sites are the best three far more strongly than it supports any particular ordering among them.

Third, the analysis confirms from another direction the observation made above about the noise criterion. Its panel in Fig. 9 shows all five lines converging to the same point as the weight approaches one, which is the signature of a criterion on which every alternative scores identically. No weight assigned to RUI, however large, can alter the ranking in this case.

### Why the groups judge differently

The unadjusted tests and group means showed a similar pattern: ITA and SAC priorities are close for most criteria, whereas the SUDO profile differs substantially. ITA and SAC are technical bodies operating under the same regulatory framework and employ specialists with related professional training. SUDO therefore warrants separate interpretation.

Its priority vector has a distinctive shape. It assigns 0.79 to airport-intrinsic criteria against 0.21 to city-related ones, an almost exact inversion of the balanced split of the other two groups, and within the airport branch it concentrates 0.85 on earthmoving volume. Within the city branch, it puts 0.55 on land accessibility and only 0.07 on distance to the demand-generating center. Read together, these numbers describe a group thinking primarily about what the project will cost to build and how soon it can be connected to the existing road network. That is a rational position for a group whose members, as reported in the subsection “Expert groups and consistency,” mostly hold planning positions in the municipal governments that would be responsible for delivering the complementary works with local budgets. The very low weight on distance to the demand center is also intelligible: the search area was constructed so that every candidate lies within 30 km of both cities, and the observed spread is narrow, from 22.1 to 27.5 km, so from a local standpoint the alternatives are all close enough and the criterion is not worth much. The federal and academic groups, judging the criteria in the abstract rather than against the specific geography, had no reason to make that adjustment.

A second difference concerns consistency rather than preference. Inconsistent judgments were not evenly distributed across the groups: three of nine experts in ITA (33%), four of 11 in SAC (36%) and eight of 13 in SUDO (62%) exceeded the 10% threshold. Since only the four-criterion comparison can be inconsistent, this measures how coherently each respondent handled six pairwise judgments among the city criteria. This gap cannot be attributed to unequal preparation, because all three groups received the same briefing material and used the same web application, as described in the subsection “Expert groups and consistency;” it is consistent instead with the regional participants having had less prior exposure to structured decision protocols of this kind. The absence of any feedback loop compounds the effect: because respondents were never shown their consistency ratio and could not revise a matrix, an incoherent set of judgments was discarded rather than repaired. This has a practical consequence for the procedure: the group that most strongly represents local interests ended up contributing the fewest valid vectors, 5 against 7 and 6, and hence the smallest share of the pooled ALL vector.

Two other applications provide limited comparative context. In Maragogi, Alagoas, Brazil, all three locally nominated experts exceeded the threshold ( $CR = 0.34\text{--}0.35$ ), excluding the local group from the aggregated weights (ITA 2019a). In metropolitan Belém, Pará, Brazil, by contrast, the four locally nominated experts produced  $CR$  values of 0.017–0.054, lower than those of the academic group (ITA 2022). The local participants were municipal officials in southwestern Paraná and Maragogi, but staff of the state land institute in Belém. Although three cases cannot establish causation, this contrast suggests that experience with structured land assessment may matter more than local affiliation itself.



If MESA is to give local stakeholders genuine weight, this suggests that briefing and interview support for the regionally nominated participants should be strengthened before the judgments are elicited, and that the facilitator role the methodology already provides for should be used more actively with these participants, rather than accepting the attrition after the fact.

## Limitations

Three limitations should be stated. The exercise reports a single region, so the weight patterns observed here, particularly the SUDO profile, cannot be generalized to other Brazilian regions without further cases. We draw on two further applications of the methodology to qualify the consistency finding, but only for that purpose; a full comparison of the priority vectors obtained across all the regions where MESA has been applied would be needed to establish whether the divergence between local and technical priorities reported here is a structural feature of the Brazilian regional airport program or a characteristic of this particular region, and that comparison is beyond the scope of this paper. The exclusion rule for inconsistent judgments, although explicit and auditable, discards information: an expert marginally above the threshold is treated like one far above it, and the alternative of returning the matrix to the respondent for revision, which Saaty himself suggests, was not supported by the elicitation tool used at the time. Finally, the ranking presented here is a technical input, not a decision. Environmental licensing, land tenure, and detailed cost estimation for the three recommended sites remain to be carried out, and any of them could still reorder the short list.

## CONCLUSION

This paper reported the application of MESA to the choice of a regional airport site for Pato Branco and Francisco Beltrão, in southwestern Paraná, Brazil. Ten candidate sites were identified inside a 550-km<sup>2</sup> search area, five were eliminated by obstacle and infrastructure constraints, and the remaining five were surveyed in the field and ranked with AHP using judgments from 33 experts, of whom 18 produced consistent comparisons.

Sites 2, 2C, and 2A were the three best-placed alternatives under every set of weights, including those of each group taken separately, and the ITA team recommended that the new airport be selected from among them. Because the ordering does not change with the weighting scheme, the recommendation is not an artefact of how the panel was composed, which matters in a decision that federal, academic, and local actors will each want to audit.

Beyond the recommendation itself, keeping the three groups separate produced two findings that a single aggregated vector would have hidden. The federal and academic experts converged on seven of the eight criteria while the regional group diverged from both on almost all of them, weighting construction cost and road access far above the rest; and the regional group was also the least internally consistent, losing eight of its 13 members to the consistency filter and therefore contributing least to the pooled priorities. Comparison with two other applications of the methodology indicates that this second effect follows the professional background of the participants rather than their being local: where the locally nominated experts were municipal officials, the loss was severe, and in a case where they came from a state technical agency, they were the most consistent group of all. Both observations concern how the panel is assembled and prepared, not how the arithmetic is done, and they are relevant to any public procedure that elicits weights from heterogeneous stakeholders.

The decomposition into global weights showed that earthmoving volume alone carries between a quarter and two thirds of the total weight, so the ranking is largely a ranking on construction earthworks, and that the noise criterion did not separate the alternatives at all in this case. The sensitivity analysis then showed that the recommended short list withstands a reduction of up to 45% or an increase of up to 109% in any single weight, while the order within the list does not: site 2 yields the first position to site 2C under moderate changes to the weights of geology or of availability of public services. We suggest that MESA applications routinely report global weights, check which criteria actually discriminate among the surviving sites, and publish a sensitivity analysis, since a criterion may be weighted heavily and still have no effect on the outcome, and a ranking may be far more secure as a set than as an order.

Further studies are recommended to evaluate the environmental, social, and economic impacts of the three recommended sites before a definitive decision is taken. Since this case was carried out, the same program has applied MESA to four other Brazilian regions, and a comparative analysis of the priority vectors and consistency rates obtained across all of them would test whether the divergence between local and federal priorities observed here is a general feature of the Brazilian regional airport program or a characteristic of this particular region.

## CONFLICT OF INTEREST

Nothing to declare.

## DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon reasonable request.

## AUTHORS' CONTRIBUTION

**Conceptualization:** Guterres MX and Alves CJP. **Formal Analysis:** Guterres MX. **Investigation:** Guterres MX and Alves CJP. **Resources:** Alves CJP. **Supervision:** Alves CJP. **Validation:** Albano CS. **Data curation:** Guterres MX. **Writing – original draft:** Guterres MX. **Writing – review and editing:** Guterres MX, Albano CS and Alves CJP. **Final approval:** Guterres MX, Albano CS and Alves CJP.

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ChatGPT (OpenAI) was used to assist the English translation of the original submission. The authors wrote and revised the present version and take full responsibility for its content.

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