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SITE SELECTION PROCESS FOR NEW NUCLEAR POWER PLANTS - A METHOD TO SUPPORT DECISION MAKING AND IMPROVING PUBLIC PARTICIPATION

Vivian B. Martins[1], Tatiana S. da Cunha[1], Francisco Fernando Lamego S. Filho[1] and Celso Marcelo F. Lapa[4]

[1] Laboratório de Impactos Ambientais - Instituto de Engenharia Nuclear
Rua Hélio de Almeida, 75
Cidade Universitária - Ilha do Fundão
Rio de Janeiro - RJ
vbmartins@ien.gov.br
tcunharj@yahoo.com.br
flamego@ien.gov.br

[4] Programa de Pós-Graduação em Ciência e Tecnologia Nucleares - Instituto de Engenharia Nuclear
Rua Hélio de Almeida, 75
Cidade Universitária - Ilha do Fundão
Rio de Janeiro - RJ
lapa@ien.gov.br

ABSTRACT

The Brazilian Energy Plan (PNE 2030) that guides the Government in formulating its strategy for expanding energy supply by 2030 highlights the need for the Brazilian electrical system have more than 4,000 MW from nuclear sources by 2025. Therefore, the Government presented a proposal to build four more nuclear power plants with capacity of 1,000 MW each, at first, two in the Northeast and two in Southeast.
The selection and site assessment are key parts of the installation process of a nuclear plant and may significantly affect the cost, public acceptance and safety of the facility during its entire life cycle. The result of this initial stage, it can even seriously affect program success.
Wrong decisions in the process of site selection may also require a financial commitment to higher planned in a later phase of the project, besides causing extensive and expensive downtime.
Select the location where these units will be built is not a trivial process, because involves the consideration of multiple criteria and judgments in addition to obtaining, organizing and managing a diverse range of data, both qualitative and quantitative, to assist in decision making and ensure that the site selected is the most appropriate in relation to safety and technical, economic and environmental feasibility.
This paper presents an overview of the site selection process and its stages, the criteria involved in each step, the tools to support decision making that can be used and the difficulties in applying a formal process of decision making. Also discussed are ways to make the process more transparent and democratic, increasing public involvement as a way to improve acceptance and reduce opposition from various sectors of society, trying to minimize the expense and time involved in the implementation of undertakings of this kind.

1. INTRODUCTION

Brazil has shown an expressive pace of economic development and this has been reflected in demand for primary energy, mainly due to an important process of industrialization and a notable population growth, combined with a accelerated rate of urbanization. A report by the Energy Research Company [1] pointed out the need for the Brazilian electrical system have more 4.000MW from nuclear source by 2025 in order to meet the country's energy needs.

So, it was presented the project to build four more nuclear power plants with capacity of 1,000 MW each, two in the Northeast and two in the Southeast, according to the needs presented in the PNE 2030 [1]. In the future, with the increasing expansion of electricity supply there is the possibility of building more plants.

In a country of continental dimensions like Brazil, the indication of a region where to start selecting a site for construction of power plants is already a big step, the selection process reduces the search area to about 20% of the total area of the country. Still, what seems to make it easier is far from trivial, because there are still to be analyzed 1.554.257,004 km^2 (almost three times the size of France).

Furthermore, several other factors make this problem complex, among which we highlight (i) the large number and diversity of factors to be considered in this type of analysis, and the consequent number and range of data and information to be managed in the process, (ii) the number of decision makers involved and their opinions about the importance of selection factors, (iii) the need for a process that optimizes the time of site selection and reduces costs, and lastly, (iv) that is transparent, i.e., that allows monitoring and involvement of all stakeholders, making it fair, democratic and minimizing resistance.

2. THE SITE SELECTION PROCESS

This article examines the process of choosing a site that has characteristics suitable for building a nuclear power plant. Problems of this type imply, ultimately, a choice: "What makes a place better than another for the facility in question?" and must take into account many and sometimes conflicting criteria1.

In general, decision-making problems with multiple criteria involve a set of alternatives that are evaluated on the basis of conflicting and incommensurable criteria [2,3]. There are two approaches to multicriteria decision problems: multi-objective and multi-attribute, the latter is the subject of this article.

Multi-attribute decision problems involving ordering of the alternatives according to their efficiency in meeting the proposed objectives, then the decision on the preferred alternative (e.g. through assessment, prioritization or selection) from the available alternatives. An alternative is usually described by a set of attributes, often conflicting, which represent properties of the alternatives analyzed. An attribute can also be defined as a measurable quality or quantity, whose value reflects the degree to which a particular goal is achieved [4]. Thus, one can say that an attribute can be used both as a decision variable and as a decision criterion.

To accomplish this ranking, it is necessary that the efficiency with which objectives are met by the various alternatives can be verified. This check is done using attributes as decision criteria, i.e., an attribute is used to measure the performance of an alternative to a goal [3]. The efficiency with which the objectives are met is measured by attributes and is the basis for comparison of alternatives.

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[1] In the context of multicriteria decision, the term "criterion" is applied both to the objectives and attributes [2,3,5].

Another important point to note is that this type of selection problem has a strong spatial component, since it involves a set of alternatives (sites), geographically defined, from which the choice is made of one or more alternatives in terms respect to a given set of evaluation criteria [6,7,8,9]. The alternatives are defined geographically in the sense that the analysis results (decisions) depend on their spatial arrangement. In this case, the evaluation criteria are associated with geographic entities and relations between them and therefore can be represented in the form of maps, from which the choice is made of one or more alternatives according to the evaluation criteria.

The use of Geographic Information Systems (GIS) is useful for dealing with this issue from another angle. From the point of view of supporting decision making, GIS can be considered as a system to support decision making involving the integration of spatially referenced data in an environment of problem solving [10]. The GIS can be considered as a digital database, with specific purposes, in which a common spatial coordinate system is the primary means of storing and accessing data and information. These systems allow the integration of a wide range of geographic technologies such as remote sensing, global positioning system (GPS) and computer-aided design (CAD), has the ability to perform many tasks using the data stored and can be integrated with techniques and analytical support for decision making.

As previously mentioned, the alternatives of this type of problem are geographically defined and criteria for evaluation of alternatives can be represented in the form of maps.

The data needed for evaluation of the criteria are most commonly organized in the GIS by separate thematic maps or sets of data. Each of these thematic maps is referred to a layer. A layer is a set of data describing a single characteristic of each location within a bounded geographical area. Only one item of information is available for each location within a single layer. The sequence of layers typically begins with a reference grid on top of which other layers containing data specific to the problem, will be added (e.g. land use, soil types, hydrography, population distribution, etc.). Each layer contains information of a different nature and can be considered as a variable, that is, it captures the variation of one attribute over the Earth's surface [3], as shown in Figure 1.

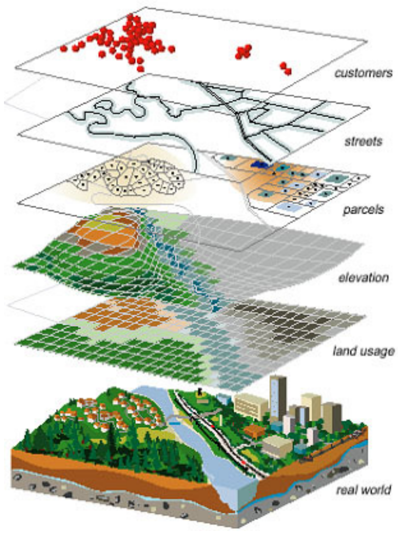

Figure 1. Types of Spatial Data (Source: ESRI)

This type of particular problem is called of Spatial Multicriteria Decision Problem.

3. SPATIAL MULTICRITERIA DECISION ANALYSIS

Multicriteria Spatial Decision Analysis can be thought of as a process that combines and transforms geographical data (input) into a resultant decision (output). Multicriteria Decision Making procedures (or decision rules) define a relationship between the input maps and the output map. The procedures involve the use of spatial data, the preferences of decision makers and manipulation of data and preferences according to specific decision rules.

To reach a decision or decisions, there is a sequential process of activities that begins with decision problem recognition and ends with recommendations. Figure 3 below shows the sequence of activities that may be involved in decision-making.

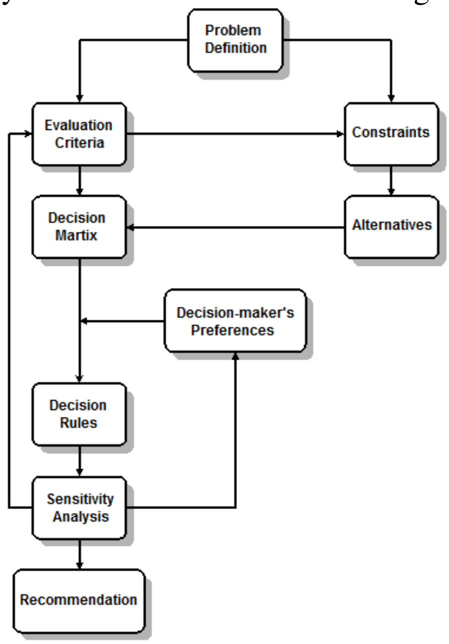

Figura 3. Framework for spatial multicriteria decision analysis [3].

The following is a summary of the steps involved in the Process of Spatial Multicriteria Decision Analysis according to [3].

3.1 Problem Definition

Any decision-making process begins with the recognition and definition of the decision problem. The decision problem is the perceived difference between the desired and existing states of a system. At this stage, the raw data are obtained, processed and examined for clues that may identify opportunities or problems. The GIS capabilities for data storage, management, manipulation and analysis offer major support in the problem definition stage.

3.2 Evaluation Criteria

Once the decision problem is identified, the spatial multicriteria analysis focuses on the set of evaluation criteria (objectives and attributes). This step involves specifying (i) a comprehensive set of objectives that reflect all the concerns (issues) relevant to the decision problem, and (ii) measures to achieve these goals. Such measures are called attributes. A measurement scale should be set for each attribute. The degree to which the objectives are met, as measured by the attributes is the basis for comparison of alternatives. The evaluation criteria are associated with geographic entities and relations between them and therefore can be represented in the form of maps. There are two types of criterion maps:

- Evaluation criterion map - is a unique geographical attribute of the alternative decisions, which can be used to evaluate the performance of the alternatives.

- Constraint map - shows the limitations on the values that attributes and decision variables may assume.

Although the desirable properties of the criteria can provide guidelines for their selection, there are no universal techniques available to determine a set of criteria. The set of evaluation criteria for a particular decision problem can be obtained through an examination of the relevant literature, an analytical study and also surveyed the opinions [11,12].

Case studies and documents from agencies or government can be used as a guide for the selection of evaluation criteria for a particular problem [3].

Another method that can be used to formulate evaluation criteria is the survey of expert opinion. According to [12], people affected by a decision or a group of experts may be asked about the criteria that should be included in decision analysis.

There are two trends in the definition of evaluation criteria [3]: the problem situation can be described in a complete or simplified manner. The difference between these two trends is primarily in the number of criteria involved and the amount of information available for the evaluation of each criterion. In a previous selection of sites for construction of a geologic repository for disposal of spent fuel from nuclear power plants in Brazil, [13] choose a simplified description, carried out by a small number of criteria. This simplification was related to the availability and quality of data, and even aware that some evaluation criteria are important to the decision problem, the necessary data were not available or were of poor quality.

When installing a nuclear power plant should be chosen criteria highlighting important features of the site for safety analysis and the way in which they were considered in the development of adequate safety margins. This set of criteria should be seen as the first step to overcome or minimize the impact of external phenomena that occur on site and that somehow influence the design features.

When siting a nuclear power plant, the goal is to protect the plant against external threats, and minimize any environmental damage and threats that may arise from their presence. Usually the selection criteria are derived from regulatory environmental and plant design requirements, beyond the interests of the project proponent, especially those related to economic issues. Additionally, are also considered factors such as impact on land use, socio-economic impacts, transportation, among others. In the evaluation of the suitability of a site for a nuclear installation, the following aspects shall be considered [14]:

- Effects of external events that occur in the region (natural or human-induced) on the plant;

- Features of the site and its environment that can influence the transfer of radioactive material released to the man;
- Population density and distribution, taking into account the need to implement contingency measures

There are several documents that provide criteria for choosing sites for building nuclear power plants, among them we can highlight: [14,15,16,17,18,19,20,21,22,23] among others.

3.2.1 Criterion Maps

Defined evaluation criteria, each criterion should be represented as a layer in the GIS database.

As already mentioned, there are two types of criteria maps: evaluation criterion map and constraint map [24,25].

An evaluation criterion map represents the spatial distribution of an attribute and is used to evaluate the performance of alternatives with respect to the goal associated with this attribute. Since constraints represent limitations imposed on decision variables (the set of alternatives). They can be used to eliminate the analysis, alternatives characterized by certain attributes and/or certain attribute values. Then constraint maps show the set of viable alternatives.

The process of generating criterion maps is based on the capabilities of GIS. The relevant data are acquired and stored in the GIS and then are manipulated and analyzed to obtain information about a particular evaluation criterion.

At this stage, the capabilities of GIS to manipulate and analyze data are used to generate inputs for Spatial Multicriteria Decision Analysis.

3.3 Alternatives

The process of generating alternatives must be based on the structure of values and be related to the set of evaluation criteria. This approach is defined by [12] as a value-focused approach and uses the values (evaluation criteria) as the cornerstone of decision analysis. In this approach, the alternatives are derived from the structure of values, that is, the alternative decisions must be generated so that the values specified for the decision situation can be better achieved [12]. This implies that the order of reasoning focuses first on what is desired, then the alternatives to get it. It is argued that values are more important than the alternatives for the decision problem. In other words, the alternatives are the means to achieve the most fundamental values.

For each alternative is assigned a decision variable. Variables are used by the decision maker to measure the performance of the alternatives. The set of decision variables define the space of decision.

At this stage, in possession of maps of evaluation criteria (factors) are generated alternative decisions. Each alternative is characterized by a vector. To formalize the problem of multi-attribute decision, the set of alternatives X can be defined in terms of decision variables, in other words, $X = \{x_{i*} \mid i = 1,2,\ldots,m\}$. The alternatives are represented by a set of cells or pixels in a raster GIS or a set of points, lines and/or polygons in a GIS vector. Then the index *i* indicates the location of the *ith* alternative. Thus, each alternative is described by its location and its criteria (attributes) values. Since the attributes are used as decision variables, it can be called the value of a criterion of *xij*, which represents the level of the *jth* attribute in relation to alternative *i*. Thus, an alternative *i* can be characterized by a vector:

$$x_{i*} = (x_{i1}, x_{i2}, \ldots, x_{in}) \text{ for } i = 1,2,\ldots,m \quad (1)$$

and levels of attributes through an alternative is represented by a vector

$$x_{j*} = (x_{1j}, x_{2j}, \ldots, x_{mj}) \text{ for } i = 1,2,\ldots,n \quad (2)$$

The input data for spatial multicriteria decision analysis (Equations 1 and 2) can be arranged in a tabular form (Table 1). The table, also called decision matrix, shows alternative-attribute relations. The matrix rows represent the alternatives. Each alternative is described by its location and its attribute data. Each attribute is recorded in a column in the decision matrix. The matrix cells contain the values of the attributes measured or evaluated with respect to alternatives.

Table 1 – Matrix alternative - attribute relationship

	Attribute 1	**Attribute 2**	**...**	**Attribute n**
Alternative 1	x_{11}	x_{12}	...	x_{1n}
Alternative 2	x_{21}	x_{22}	...	x_{2n}
...	...	...	...	...
Alternative m	x_{m1}	x_{m2}	...	x_{mn}

Besides the decision variables, constraints are also defined. These constraints represent limitations imposed on the decision space. They determine the set of viable alternatives. In terms of GIS, constraints are used to eliminate the process points, lines, polygons, and/or rasters characterized by certain attributes and/or attribute values.

Given the set of alternatives for the decision problem, this can be limited through the imposition of restrictions on attribute values (non-spatial constraints) or on the attributes of location (spatial constraints).

As stated earlier, constraints are limitations imposed by nature or by humans (rules, laws, etc.), which do not allow certain actions are taken [26]. The specification of constraints is usually based on available resources and regulations and involves professional judgments or value. In Brazil, as in many countries, there are a number of rules, laws and standards, imposed by the urban, transport and environmental planning, among others. In general, to meet these standards is necessary that the alternatives meet the specific values with respect to all criteria, or to some specific evaluation criteria.

When evaluating alternatives with respect to the restrictions, does not consider trade-offs among the evaluation criteria, it is said that this assessment is not compensatory. On the other hand, if they are considered trade-offs between various criteria says that the evaluation process is compensatory.

The process of non-compensatory evaluation can still be classified conjunctive (when an alternative is accepted if it meets specific standards or limit values for all constraints) or disjunctive (when an alternative is accepted if present high figures in at least one of criteria under consideration).

3.4 Criteria Weights

At this stage, the preferences of decision makers regarding the evaluation criteria are incorporated into the decision model. Preferences are expressed in terms of relative importance weights assigned to evaluation criteria considered. Broadly speaking, the purpose of weight criterion (goal or attribute) is to express the importance of each criterion in relation to others. The derivation of the weights is the key step to adequately consider the preferences of decision makers. Given the set of alternatives, attributes and associated weights, the input data can be organized in the form of a decision matrix.

Multicriteria decision problems typically involve criteria that vary in importance for decision makers [3]. Therefore, it is necessary to have information about the relative importance of each criterion over another. This is achieved by assigning a weight to each criterion. Obtaining the weights is an important step in the understanding and use of the preferences of decision makers. A weight can be defined as a value assigned to an evaluation criterion, which indicates its importance in relation to other evaluation criteria considered [3]. The higher the weight, the more important criterion for the overall assessment.

Are proposed in the literature several methods for assigning weights to criteria, based on judgments of decision makers, among them we can mention the trade-off method [12], the ratio method [27], Brainstorm [28,29], Delphi [30,31,32,33] and the Analytic Hierarchy Process (AHP) [34,35,36]. These methods differ in their theoretical basis, the degree of difficulty of application and understanding by those involved and accuracy. Another important feature to be evaluated is how the method can be incorporated into decision analysis based on GIS.

3.5 Decision Rules

This step brings together the results of the previous three steps. The one-dimensional measures (layers) and judgments (preferences) should be integrated to provide an overall assessment of the alternatives. This is accomplished by a decision rule or appropriate aggregate function. It is this decision rule that dictates how best to order the alternatives or decide which alternative is preferred over others.
The evaluation criteria, feasible alternatives and the preferences of decision makers are combined using the decision rules. They provide the basis for the ordering of decision alternatives and for choosing the most appropriate alternative, integrating data and information on alternatives and preferences of decision makers in an overall assessment.

The goal of the multi-attribute decision analysis is to choose the preferred alternative or alternatives in descending order of preference. There are numerous decision rules that can be used to treat this type of problem.

3.6 Recommendation

The end result of a decision process is a recommendation for future action. The recommendation should be based on the classification of the alternatives and sensitivity analysis. It may include a description of the best alternative or a group of alternatives considered candidates for implementation. Visualization techniques are of great importance in presenting and communicating results to decision makers and interest groups.

Although each step of the spatial multicriteria analysis involves both GIS and multicriteria methods, the steps differ in the extent to which these two methodologies are used. In the early stages, the GIS methods are more important, while in the latter stages, the multicriteria methods play a major role. Thus, two considerations are important for spatial multicriteria decision analysis:

1. the GIS capabilities for the acquisition, storage, retrieval, manipulation and analysis of data and,

2. the MCDM capabilities for aggregating the geographic data and decision maker's preferences into unidimensional values of alternative decisions.

The steps listed above are repeated in each new phase of the project as shown in Figure 5. As the process advances, are reduced scales of spatial data in order to increase the detail of the analysis [21]. The standard CNEN NE-6.06 [37] provides, for example, the scales of work that should be used at each stage of a process of selecting sites for radioactive waste disposal, which follows essentially the same phases of a process of selecting sites for other nuclear installations, for example, plants for energy production.

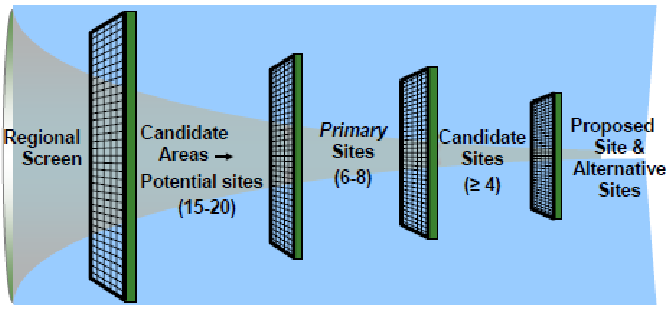

Figure 5: Site selection process. Source: [38]

4. STAKEHOLDERS INVOLVEMENT

Accidents like Three Mile Island and Chernobyl, and more recently Fukushima, attracted the interest of society to nuclear issues. The development of media that allow monitoring of events and their consequences in real time, such as TV and internet, created an awareness that perhaps did not exist previously. Furthermore, considerations about the environmental impacts of various energy options are in evidence.

According to the IAEA [39], stakeholders are defined as those who are interested in a particular issue or decision. There are usually two types of stakeholders: the internal, who are involved in decision making and external, that are most often affected, both directly and indirectly, by potential project outcomes.

The expectations of stakeholders regarding the right to participate in decisions are something that the nuclear community should be concerned. Issues such as location and construction of a nuclear power plant are no longer, in large part the domain of a closed community of technicians and executives of the installation. All stakeholders in decisions of the nuclear area should have the opportunity to participate fully and effectively their. Only full and open engagement of various stakeholders will serve to improve decision making, as well as promoting the common interest in ensuring the safety of nuclear installations [39].

Experience has shown that in democratic societies to build a new nuclear plant is not possible without the active consent of at least the population most directly affected [40].

5. CONCLUDING REMARKS

The main challenge for this type of formal analysis, based on the use of Geographic Information Systems, is to create a model that represents the real conditions of the sites analyzed and feed him with data about each relevant criterion for decision making.

The amount of geospatial data available today is enormous. These data can be obtained using different means of collection (GPS, aerial imagery, etc.) at different levels of accuracy. The high demand and the ease of play data in digital media has created redundancies in the production and storage of these data, making the stage of development of the database the most critical, long and costly of the applications of GIS. In order to organize the production of data, one must standardize and regulate this production.

Brazil took an important step in this direction with the publication of Decree Nº. 6.666 [41]. This Decree establishing the National Infrastructure of Spatial Data - INDE with the objective of promoting the proper ordering in the generation, storage, access, sharing, dissemination and use of geospatial data source in the federal, state, county and municipal levels, and also promote the use, in the production of geospatial data, of the standards and regulations approved by the National Commission Cartography [42].

In addition to regulation, another important factor that overloads the step of preparing the data base is the difficulty of integrating these data, which are mostly scattered and in different formats.

Thus, it is necessary to integrate these different geospatial data available, in order to provide the user a unified view of data, even if they are in different databases, allowing queries and analysis. This integration also allows the solution of specific problems of geospatial data, as differences between coordinate reference systems and planimetric accuracy. Proper integration, allows obtaining a more rapid, accurate and less expensive geospatial information.

INDE also want to answer these questions, because it proposes to categorize, integrate and harmonize the existing geospatial data in Brazilian government institutions, which produce and maintain this type of data, so that they can be easily located, accessed and exploited for different uses, for any customer that has Internet access [42].

The INDE will be an important tool for efficient planning, management and development of public policies such as the location of nuclear facilities.

Another important point is the quality of geospatial data. This quality can be measured by consulting the metadata related to geospatial data. Quality metadata are data that describes the quality of data. Quality is an essential or distinguishing characteristic necessary for cartographic data in order to make them suitable for use. The existence of measures of data quality is essential to assess the reliability of the results obtained from the applications were made with these data. The most important quality metadata include lineage, accuracy, logical consistency and completeness. Besides these there are other elements such as cloud cover and error [43].

As data quality directly affects the reliability of results of the analysis it is important to consider in decision making. One way to do this can be through the use of a Quality Factor (QF), where data considered of higher quality would receive a higher score than data considered as having lower quality.

In the end, when assigning weights to the selection criteria, these weights would be a result of their importance (obtained through the value judgments of stakeholders, experts or not) weighted by the quality factor.

So:

$$WC_a = \sum I_a \times QF_a \tag{3}$$

Where,

WC_a represents the Weight Criterion a
I_a represents the Importance of the Criterion a and,
QF_a represents the Quality Factor of the data used to evaluate the criterion a.

The consideration of the quality of the metadata have beneficial effects because a better understanding of the technical limitations imply a better understanding of the adequacy of the data used and decision-making more accurate and better informed, essential to ensure the safety of the proposed project.

6. CONCLUSIONS

Due to the magnitude of delays and/or stakes and potential consequences related to any decisions about the location of the installation, it is important to conduct a formal analysis that can assist the professional intuition of the decision maker. This analysis should help to understanding what characterizes the "best" site as well as providing the necessary information for regulatory processes.

For this formal analysis structure is needed to integrate and incorporate information on the selection criteria to the value judgments of stakeholders in order to establish a comprehensive and transparent assessment of the global implications of each alternative.

Historically, most analysis of site selection did not happen this way. The story of the nuclear energy use is full of cases that demonstrate how the absence of a formal analysis, the lack of a solid database on the characteristics of the site and no account of judgments and opinions of stakeholders can lead to breakdowns, delays and even preventing of nuclear projects [44,45].

The use of a formal analysis, transparent and participatory has been the approach used in recent work of site selection for a variety of facilities [21].

In this context, Spatial Multicriteria Decision Analysis allows the effective implementation of stakeholder participation in decision-making through the use of weights assigned to the selection criteria or, as mentioned above, by identifying criteria relevant to stakeholders and ways to measure them.
As shown previously, assigning weights to the criteria can be done using various tools, like Analytic Hierarchy Process, Brainstorm, and Delphi among others.

Problems related to difficulties in obtaining spatial data, which are discussed in the final considerations do not prevent use of the methodology. Martins [13] obtained consistent results even with a small number of criteria due to the unavailability of data, which shows that the methodology is applicable even when there is little information, helping decision makers in situations with this degree of difficulty. In these cases, the analysis provides a formal framework for dealing with the decision problem, organizing the tasks to be performed and the information available to perform them, as well as helping to visualize the problem as a whole, thus allowing the identification weaknesses of the process and the search for tools to deal with them.

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