IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 7, 2020, accepted March 1, 2020, date of publication March 9, 2020, date of current version March 20, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2979666

Selecting Projects on the Brazilian R&D Energy Sector: A Fuzzy-Based Approach for Criteria Selection

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This work was supported in part by the Higher Education Improvement Coordination (CAPES) of Brazil, in part by the National Council for Scientific and Technological Development (CNPq) of Brazil, in part by the Research Supporting Foundation of Minas Gerais State (FAPEMIG) of Brazil, and in part by the São Paulo Research Foundation (FAPESP) of Brazil.

ABSTRACT Many companies around the world rely on R&D to better their chances for profit and permanence in a dynamic market. To keep up with ongoing changes, many ideas arise and some transform into projects. Since resources are limited, organizations seek to select only the most suitable projects to meet their objectives. This is an old practice. However, project portfolio characteristics have changed. The portfolio objectives of today go beyond profit: strategy, environment and society have also become important, along with many other decision criteria. Computational power has also been enhanced, making multi-data decision approaches more feasible, even for small-profit organizations. In the last half century, many authors have proposed multicriteria decision making (MCDM) methods for project portfolio selection (PPS) for Research and Development (R&D). Nevertheless, only a few paid due importance to the criteria used, which would be a central issue on any multicriteria decision. Thus, in order to contribute to the R&D PPS field of study, this work investigates the hypothesis that the criteria used in R&D PPS can be selected in an uncertain environment, according to their influence and importance. To do so, we propose a novel MCDM approach for criteria selection, that integrates Fuzzy-based DEMATEL (Decision Making Trial and Evaluation Laboratory) and Fuzzy-AHP (Analytic Hierarchy Process) Extend Analysis methods. We are also presenting a case study for a representative electrical-public Brazilian R&D organization, that from 2008 to 2018 managed R&D project portfolios valued at around US$ 1.2 billion. The results reflect current Brazilian concerns on the prioritized criteria, such as environmental, social and technical criteria, especially on the face of the disaster occurrences that took place on the media on the last years. In an overall manner, the results provide guidance on the topic and facilitate knowledge accumulation and creation concerning the criteria selection process in MCDM-based R&D PPS.

INDEX TERMS AHP, criteria selection, DEMATEL, fuzzy, MCDM, project portfolio.

I. INTRODUCTION

Project-driven companies that depend on innovation have the obligation to develop and implement new products and processes to achieve a continued competitiveness and a strong presence in the market. So, research and development (R&D) is the main task in their strategic management framework [1]. According to UNESCO Institute for Statistics (UIS), the annual global spending on R&D projects reached a record of almost US$ 1.7 trillion in 2018 [2]. However, Balachandra and Friar [3] reminds us that in 1991, around 90% of a sample of 16,000 new product development projects failed. It is an old reference, but the problem and the numbers persist until today, at least for the pharmaceutical segment, which registered a 88.3% of clinical failure rate in 2007 [4]. To avoid project failure, companies have to find better ways of managing and selecting their projects portfolios, using scarce resources with the objective to maximize some utility measure or benefit or, in other cases, minimize the risk or costs of their projects [5].

The associate editor coordinating the review of this manuscript and approving it for publication was Emre Koyuncu.

According to Shou and Huang [6], all organizations across the globe insert about 90% of their projects in a context of multiple projects. Thus Project Portfolio Selection (PPS) may be modelled as a knapsack problem, since a set of projects compete with each other for scarce resources (human, time, budget) under the sponsorship of a particular organization [7]. Regardless of the adopted methodology, project portfolio management (PPM) aims to ensure that organizations perform only the right projects, rather than correctly executing any possible project.

In contrast to former R&D PPS applications [8], [9], the propagation and popularization of the computational power of today also enables the proposition of models and software that were not viable to R&D organizations and practitioners in the past. This happens not only in PPS, but in almost all decision-making fields [10], [11].

The decision-making process in Research and Development (R&D) Project Portfolio Selection (PPS) is quite similar to decision-making in other fields. The uniqueness of each portfolio is the reason why there are several scientific papers addressing different methodologies for R&D PPS [12]–[17]. The main characteristics of R&D PPS are: (a) the spending on projects represents sizable investments; (b) those are investments that companies make in their future; thus, (c) the projects must be tied to corporate strategy; (d) the returns from R&D projects have long lead times, are risky and multidimensional in nature; and (e) the environment is turbulent and the results uncertain [1], [13], [18]. These unique features make it difficult to make good or optimal decisions.

Multi-criteria Decision-Making (MCDM) methods are recurrent on R&D PPS. MCDM supports the decision-makers on ranking and/or choosing the best alternatives on the basis of several conflicting criteria. They range from simple [17] to complex approaches [18], from usual [19] to unusual [20], and from individual [1] to integrated ones [21].

However, despite being a scientifically active topic, Afshari [22] states that in the literature most of the reviewed studies on project selection do not provide a systematic method for criteria selection. Neglecting the use of an appropriate and systematic criteria selection technique might cause an inaccurate result in the final decision and, consequently, the validity of the MCDM method may be compromised. The PPS process may present difficulty in measuring certain objective goals and criteria are difficult by distinct value [23]. It makes the establishment of a proper system crucial in identifying the criteria and finding the relative importance for selecting R&D projects. Thus, adding a systematic method for criteria identification and selection, would induce more satisfactory results [24].

Hereby, the main objectives of this work are to propose, verify, and validate an integrated fuzzy-based AHP-integrated to-DEMATEL approach, suitable for criteria selection and, to the best of our knowledge, unexplored in the context of project selection. Despite the individual benefits of both AHP and DEMATEL methods, the proposed approach simultaneously evaluates the criteria according to their overall importance and influence over each other, considers the uncertainty related to data imprecision, do not let residual weights on expandable criteria, and is easy to code and to be used by small-sized R&D organizations.

The usage of DEMATEL also makes it easier to assemble the criteria in a hierarchical structure, one of the first steps of AHP and fuzzy-AHP approaches. In fact, this is one of the greatest advantages of Fuzzy-AHP-DEMATEL, when compared to the commonly used DEMATEL-ANP (Analytic Network Process) approaches.

Thus, this work only focus on the criteria selection step. We do not contemplate in this work other relevant steps for project portfolio management, such as criteria identification project selection step, scheduling, and others.

The remaining of this paper is arranged as follows: Section 2 reviews the literature on MCDM-based R&D PPS. Section 3 presents the proposed method and a real Brazilian case is summarized and discussed in Sections 4 and 5. Finally, the conclusions are provided in Section 6.

II. LITERATURE REVIEW

A project portfolio is a set of projects, programs and subportfolios that are managed together in order to achieve the organization's strategic objectives [8], [25]. According to Tervonen *et al.* [26] and Liesiö *et al.* [27], a project portfolio $p \subseteq X$ is a subset of the m project proposals $X = \{x^1, \ldots, x^m\}$, with all possible portfolios represented by the power set $P = 2^X$. The decision-makers evaluate the m proposals according to n criteria $i = 1, \ldots, n$ and the performance of each project x_j on criterion i, say v_i, is denoted by v_i^j. Equation 1 expresses the overall value of project x^j.

$$V(x^j) = \sum_{i=1}^{n} w_i v_i^j \tag{1}$$

The preference of a project over the others is directly related to their overall value, with w_i measuring the relative importance of the i^{th} criterion. The decision-makers should scale all weights $w = (w_1, \ldots, w_n)^T$ in a way that $w \in W = \{w \in \mathbb{R}^n | w_i \geq 0, \sum_{i=1}^{n} w_i = 1\}$. With constant and precise values for criteria weights w, the best portfolio is the one that maximizes the portfolio's overall value, which is the sum of all overall values of its projects and can be captured by the following additive-linear function

$$\max_{p \in P} V(p, w, v) = \max_{z(p)} \left\{ \sum_{x^j \in p} \sum_{i=1}^{n} w_i v_i^j = z(p)^T v w \right\} \tag{2}$$

where $z(\bullet)$ is a bijection $z : P \to \{0, 1\}^m$ as such that we reject the project proposal when $z_j(p) = 0$ if $x^j \notin p$ and accepted when $z_j(p) = 1$ if $x^j \in p$.

However, the simple additive weighting expression may not represent the differences among the criteria, or even the influence and interactions of one over the others. In that case, different Multi-attribute Decision Making (MADM) approaches may weight the n criteria. The literature classifies

MCDM approaches into many categories, depending on the classification criteria. Regarding the nature of the alternatives, it may be a multi-objective decision-making (MODM) method, a multi-attribute decision-making (MADM) method, or a combination of both [28], [29]. In MODM methods there are no predetermined alternatives and the methods select the optimal alternative among an infinite and continuous number of possibilities, which may also considers constraints. Generally, mathematical approaches are considered as MODM methods. Examples of mathematical approaches are: linear programming, integer linear programming, integer non-linear programming, goal programming, and multi-objective programming [30]. On the other hand, MADM methods deal with a discrete and finite number of alternatives, which are designated by a predetermined set of criteria. Thus, the main task of MADM methods is to perform a rational selection, assessment and ranking among the feasible possibilities [31].

In general, MADM has represented one of the fastest growing issues in several disciplines. The main problem is how to analyze a collection of alternatives influenced by several conflicting criteria [31], [32]. This is why it has grown as a part of operational research area, concerning the design of computational and mathematical tools, techniques, models or methods that supports the subjective evaluation of criteria performance made by decision makers [31], [33]–[35]. MADM methods help to improve the decision quality by making it more explicit, rational and efficient [29]. These methods also facilitate the negotiation, quantification and communication of priorities [28]. DEMATEL (Decision Making Trial and Evaluation Laboratory) and AHP (Analytical Hierarchy Process) are relevant examples of MADM methods.

DEMATEL is a well-known MADM method created in the early 70s by the Geneva Research Centre of the Battelle Memorial Institute to visualize causal relationships between elements in a matrix [36], [37]. In PPS, DEMATEL is useful to analyze cause-effect relationships between projects and between selection criteria.

For instance, Lin and Wu [38] have developed a MADM approach for R&D where fuzzy-DEMATEL separates the involved criteria into cause and effect groups, helping the decision makers focus on those criteria that provide greater influence. They also present an empirical study in the context of R&D. On the other hand, Altuntas and Dereli [39] have employed DEMATEL to find causal relations among projects. They also present a case study in a Public PPS context. In a more structured way, DEMATEL can be also integrated into other MADM approaches, in order to weight criteria and projects, such as the work of Büyüközkan and Öztürkcan [40], that used DEMATEL to construct interrelations among criteria and then ANP was used to weight the criteria. In fact, DEMATEL-ANP is common variation of DEMATEL method in PPS. It is also true for overall DEMATEL applications, since the combined use with ANP corresponds to around 44.5 % of all DEMATEL approaches [41].

TABLE 1. Advantages and disadvantages of classical DEMATEL.

Advantages	Disadvantages
It points out cause-effect relationships between criteria/projects, by analyzing mutual influences (with both direct and indirect effects).	We can analyze the criteria or projects by their interdependence alone.
The Influential Relation Map (IRM) makes possible interrelationship analyzes.	The judgements from different experts are not weighted when aggregating individual assessments into group assessments.
We can use DEMATEL to rank the criteria/projects and also to evaluate their criticality. The criteria/projects are evaluated by their interactions and dependencies. Unlike other methods that assumes dependencies with equal weights (such as ANP), in DEMATEL these dependencies are weighted.	It cannot take into account aspiration level of alternatives (such as GRA and VIKOR), nor obtain partial ranking orders of alternatives (such as ELECTRE approaches).

In the context of R&D PPS, we have found two cases, both using DEMATEL-ANP approaches to weight the criteria. In the first article, Jeng and Huang [42] use a modified Delphi method to refine and validate the criteria, prior to using DEMATEL-ANP. In the second article, by Cheng *et al.* [21], a DEMATEL-Fuzzy-ANP calculates preference weights of the criteria and then COPRAS-G method and fuzzy gray relations were employed to resolve conflicts that arose from differences in information and opinions. In fact, many authors couple DEMATEL and ANP to solve real world problems in project management, such as Karamoozian *et al.* [43]. According to Si *et al.* [41], solely using DEMATEL has advantages and disadvantages, which are shown on Table 1. The disadvantages can be overcome by integrating DEMATEL to other MCDM methods.

On the other hand, AHP is an easy and well-known MCDM method that allows the decision makers to deal with complex situations and with different levels of subjectivity. Saaty [44] is the first to introduce AHP, an article that received more than 8.000 citations to date and that summarizes all advantages of AHP in simplicity and clarity. It is the most used MADM method in decision-making, appearing in many recent articles and in a variety of scientific fields [45], [46]. Only in Scopus®, more than 33 thousand articles result when searching for "Analytic Hierarchy Process" OR "AHP". Among the MCDM Methods used in R&D PPS, AHP and its variations are one of the most used.

In R&D PPS, AHP is the most appreciated MADM method. The most cited articles using AHP are [8], [13], [47]. The first two, in 1986 and 1987 propose an extension of the method AHP for industrial R&D project selection, linking it to a spreadsheet model. The last one, in 1988, introduces cost-benefit analysis and 0-1 linear integer programming, along with the AHP spreadsheet model, for resource allocation [13], [47]. Papers from other authors can also be highlighted, namely Hsu *et al.* [48] that presented a fuzzy multiple criteria approach for the selection of government-sponsored R&D projects. They also report the experience in applying it at a national research institute in Taiwan. In this case, AHP was used to evaluate multiple objectives

TABLE 2. Advantages and disadvantages of classical AHP.

Advantages	Disadvantages
It weights alternatives according to their relative and overall importance's.	The criteria or projects are solely analyzed by their importance over each other.
It is able to consider hierarchical structures, which may reflect the decision reality in most cases.	Large comparison matrices (usually more than 8 alternatives) are confusing and tiring to be responded, which may result in long and inaccurate processes and results.
It greatly deals with qualitative judgments, which are commonly used to compare criteria and projects in many organizational environments.	Quantitative data may required preprocessing prior utilization.
It features a consistency index, which helps decision-makers on completing the matrices	The computational and personal effort may be considerable to large problems.

according to the expectations from various interest groups, and a fuzzy approach is employed to score the subjective judgment of the experts. Kumar [49] go further with judgment quantification, proposing an AHP-based system for R&D project evaluation that employs formal tools in quantification of subjective evaluations where expert judgement is involved. Many articles coupling AHP and fuzzy logic were found, for example: Wang *et al.* [50] developed a system for evaluating the outcomes of multidisciplinary R&D projects which is structured as a "vertical" AHP with "horizontal" fuzzy scoring. Imoto *et al.* [51] employed a principal component model, dual scaling AHP and fuzzy regression analysis to evaluate proposed research projects for single or plural fiscal years. Tolga and Kahraman [52] integrated the fuzzy AHP with a fuzzy real options valuation model for the evaluation of R&D projects. AHP can also be found staging other approaches that involve several MCDM methods and/or mathematical models, such as Rabbani *et al.* [16], that proposed a comprehensive 0-1 linear goal programming model for R&D project selection, where AHP is used to calculate the quality score of each project. Conka *et al.* [12] implemented and combined AHP, Data Envelopment Analysis (DEA) and Value Tree Analysis (VTA) in a model to determine the efficient and feasible projects among the alternative R&D projects. AHP and DEA also appears on the work of Karasakal and Aker [53], to evaluate R&D projects. Lastly, the most recent article considered in R&D PPS uses AHP as an individual approach, along with criteria and framework adapted from those recommended by the Project Management Institute [14].

AHP is also a pairwise comparison method, just like DEMATEL, however, it ranks the alternatives according to their importance. According to [14], [54], it also features advantages and disadvantages, which are presented by Table 2.

III. METHODOLOGY

A. FUZZY-BASED BACKGROUND

A fuzzy set of a discourse universe U is characterized by a membership function μ_A, which takes the values in the unit interval [0, 1]. It is an extension of classical set theory and the operations are themselves extensions of the fundamentals set theory operations of complement [55].

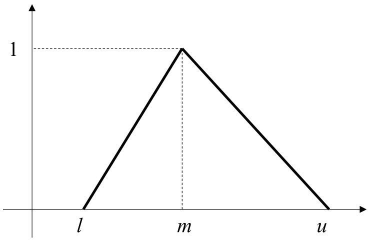

FIGURE 1. Triangular membership function.

$$\mu_A : U \rightarrow [0, 1] \tag{3}$$

In MCDM approaches, fuzzy-logic has the role of tackling the uncertainty of data imprecision. Almost all fuzzy-MCDM approaches will start with the fuzzification of crisp values, which are assigned by decision-makers or data collecting routines. Then, the operations of the method will be entirely or partially (more common) performed in a fuzzy environment and then, the fuzzy sets will be reconverted into crisp value, throughout a defuzzification method.

The triangular membership function is the most common one in MCDM-based R&D PPS applications [56]. It is defined by a lower limit (l), a middle value (m), and an upper limit (u), where:

$$\mu_A(X) = \begin{cases} 0, & x \leq l \\ \dfrac{x-l}{m-u}, & l < x \leq m \\ \dfrac{b-x}{b-m}, & m < x < u \\ 1, & x \geq u \end{cases} \tag{4}$$

The concept of fuzzy sets has been largely applied to DEMATEL approaches, in order to tackle the vagueness of human judgment [21], [38], [41]. Generally, the literature use two types of fuzzy-DEMATEL models. In the first one, DEMATEL and fuzzy logic are used, but implemented independently. In this model, the conversion of fuzzy numbers into crisp numbers is made just after setting the group direct-influence fuzzy matrix. In the second model, fuzzy logic and DEMATEL are fully coupled. Fuzzy numbers deal with the vagueness of human judgment and imprecision involved in the influence degree estimation. The defuzzification occurs at the end of DEMATEL application, just before displaying the Influential Relation Map (IRM) [41]. Similarly, incorporating fuzzy logic to the judgments of AHP is the most common way to integrate AHP and fuzzy logic. Such the as in the way Hsu *et al.* [48] used it and presented a fuzzy multiple criteria approach for the selection of government-sponsored R&D projects. They also report the experience in applying it at a national research institute in Taiwan. Here, AHP was used to evaluate multiple objectives according to expectations from various interest groups, and a fuzzy approach is used to score the subjective judgment of the experts. Among all AHP variations, the Extent Analysis Method, proposed by Chang [57] is one of the most effective and tested ones. In R&D, Mohanty *et al.* [56] have used the Extent Analysis Method to select project portfolios, however it is coupled with ANP, a general variation of AHP.

B. THE PROPOSED FUZZY-MADM APPROACH

In this work, we extend the AHP and DEMATEL integration proposed by Khazai *et al.* [58]. Thus, instead of performing a crisp integration, we do it in a fuzzy environment. Aside from the advantage of introducing uncertainty to the model, the AHP hierarchical structure is also facilitated, as well as the possibility to assign null weight to expandable criteria. In the model we propose, classic DEMATEL and AHP models are still partially implemented separately, as individual approaches. Nevertheless, steps recently added in both methods, as well as adaptations made to the fuzzy environment, are also considered by the models. To the best of the authors' knowledge, this work has not appeared in the literature.

The formulating step-by-step of the proposed method follows, as well as the references for each step.

Steps 1, 2, 3 and 4 are recurrent fuzzifications of classical DEMATEL [21], [39]–[41]. Step 3.5 is a fuzzification of an optional step only found on crisp DEMATEL. It is a novelty of this research and a recommended step for large matrices, which is the case of some criteria selection in R&D PPS. Step 5 provides the most used defuzzification method in fuzzy-based DEMATEL. Step 6 comes from classic DEMATEL and presents the IRM. Once the IRM is built, the decision-makers may establish a hierarchy with all criteria available, in step 6.5. Steps 6.5, 7 and 8 are presented by classic AHP [44], [59], [60]. Steps 9 to 14 introduce the concept of Fuzzy Extent Analysis [61]. Step 15 shows us how to extract influence coefficients from DEMATEL and how to combine them with the importance coefficients obtained in Step 14. Thee stages compose the whole process, DEMATEL for the first, AHP as the second, and their integration in the third one.

1) STAGE 1

Step 1: Generate the group direct-influence fuzzy matrix $\tilde{C}$. If there are n criteria in the evaluation system, a group of experts specify the degree of direct influence of each criterion i on each criterion j. First, an integer scale with four levels is used: no influence (0), low influence (1), medium influence (2), high influence (3), and very high influence (4). Then, the integer scale is converted into a fuzzy linguistic scale, in order to tackle its vagueness. If a triangular membership function is used, then an individual direct-influence matrix C_k is converted into a individual direct-influence fuzzy matrix $\tilde{C}_k$ for l experts. Later, if there is a decision group, the l direct-influence fuzzy matrices are aggregated and the group direct-influence fuzzy matrix $\tilde{C}$ is obtained. The triangular membership functions assumes the following values: no influence $(0, 0, 1)$; low influence $(0, 1, 2)$; medium influence $(1, 2, 3)$; high influence $(2, 3, 4)$; and very high influence $(3, 4, 4)$ [62].

$$\tilde{C}_k = [\tilde{c}^k_{ij}]_{nxn} = \begin{bmatrix} 0 & \tilde{c}^k_{12} & \cdots & \tilde{c}^k_{1j} \\ \tilde{c}^k_{21} & 0 & \cdots & \tilde{c}^k_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{c}^k_{i1} & \tilde{c}^k_{i2} & \cdots & 0 \end{bmatrix}_{nxn} \tag{5}$$

$$\tilde{c}_{ij} = \frac{1}{l}\sum_{k=1}^{l} \tilde{c}^k_{ij} \tag{6}$$

$$\tilde{C} = [\tilde{c}_{ij}]_{nxn} = \begin{bmatrix} 0 & \frac{1}{l}\sum_{k=1}^{l}\tilde{c}^k_{12} & \cdots & \frac{1}{l}\sum_{k=1}^{l}\tilde{c}^k_{1j} \\ \frac{1}{l}\sum_{k=1}^{l}\tilde{c}^k_{21} & 0 & \cdots & \frac{1}{l}\sum_{k=1}^{l}\tilde{c}^k_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{l}\sum_{k=1}^{l}\tilde{c}^k_{i1} & \frac{1}{l}\sum_{k=1}^{l}\tilde{c}^k_{i2} & \cdots & 0 \end{bmatrix}_{nxn} \tag{7}$$

Step 2: Obtain the normalized group direct-influence fuzzy matrix $\tilde{N}$.

$$\tilde{N} = \left[Min\left(\frac{1}{\max\limits_{1\leq i\leq n} \sum_{i=1}^{n} \left|c_{ij3}\right|}, \frac{1}{\max\limits_{1\leq j\leq n} \sum_{j=1}^{n} \left|c_{ij3}\right|} \right) \right] \odot \tilde{C} \tag{8}$$

Step 3: Construct the total-influence fuzzy matrix $\tilde{T}$ summing the direct and all indirect effects from $\tilde{N}$.

$$\tilde{T} = \lim_{i\to\infty} (\tilde{N}^1 \oplus \tilde{N}^2 \oplus \cdots \oplus \tilde{N}^i) = \sum_{i=1}^{\infty} \tilde{N}^i = \tilde{N} \otimes (1\Theta\tilde{N})^{-1} \tag{9}$$

when $\lim\limits_{i\to\infty} \tilde{N}^i = 0$.

Step 3.5 (Optional): Obtain the Inner Dependence Fuzzy Matrix $\tilde{G}$. Just after obtaining the total-influence fuzzy matrix $\tilde{T}$, $\tilde{G}$ is obtained by normalizing $\tilde{T}$. Relations whose effects in $\tilde{T}$ are larger than a threshold $\tilde{\alpha}$ are displayed in $\tilde{G}$.

$$\begin{aligned} \tilde{G} &= [\tilde{g}_{ij}]_{nxn} \\ &= \begin{cases} \tilde{g}_{ij} = \dfrac{(k_{\max} - k_{\min}) \odot (\tilde{t}_{ij}\Theta \min t_{ij1})}{\max t_{ij3} - \min t_{ij1}} & \text{if } \tilde{t}_{ij} > \tilde{\alpha} \\ \tilde{g}_{ij} = 0, & \text{if } \tilde{t}_{ij} < \tilde{\alpha} \end{cases} \end{aligned} \tag{10}$$

where k_{min} is the lowest and k_{max} is the highest possible scores in a given scale, which are usually $k_{min} = 0$ and $k_{max} = 4$. The threshold $\tilde{\alpha}$ is used to filter omittable criteria out. It can be determined by many ways, such as performing brainstorms with experts or tanking the average values from matrix $\tilde{T}$ [21], [41].

Step 4: Compute the fuzzy dispatcher group $\tilde{D}$ and fuzzy receiver group $\tilde{R}$. For the Inner dependent fuzzy matrix $\tilde{G}$, calculate the sum of rows $\tilde{D}$ and columns $\tilde{R}$ for the elements $\tilde{g}_{ij}(i, j = 1, 2, \ldots, n)$.

$$\tilde{D} = \left[\tilde{d}_i\right]_{nx1} = \left[\sum_{j=1}^{n} \tilde{g}_{ij}\right]_{nx1} \tag{11}$$

$$\tilde{R} = \left[\tilde{r}_j\right]_{nx1} = \left[\sum_{j=1}^{n} \tilde{g}_{ij}\right]_{nx1} \tag{12}$$

Step 5: Convert the fuzzy numbers into crisp numbers using a defuzzification method. The CFCS (Converting Fuzzy data into Crisp Scores) is the most used defuzzification method in fuzzy-based DEMATEL. This defuzzification method offers greater crisp values with greater membership function and distinguishes two symmetrical triangular fuzzy numbers with the same mean [38], [63]. When applied to $\tilde{D}$ and $\tilde{R}$, the defuzzied D and R values are obtained. Equations (13) and (14), as shown at the bottom of this page.

where d_j is the defuzzified value of $\tilde{d}_i = (d_{i1}, d_{i2}, d_{i3})$ with $L_D = \min d_{i1}$, $U_D = \max d_{i3}$, $\Delta_R = U_D - L_D$ and r_j is the defuzzified value of $\tilde{r}_j = (r_{j1}, r_{j2}, r_{j3})$ with $L_R = \min r_{j1}$, $U_R = \max r_{j3}$, $\Delta_R = U_R - L_R$.

Step 6: Create an Influential Relation Map (IRM). First, calculate the "Prominence" horizontal axis $(R + D)$ and the "Relation" vertical axis $(R - D)$. If $(r_j - d_j)$ is positive, then Criterion c_j belongs to the cause group and has net influence on the other criteria; if $(r_j - d_j)$ is negative, then criterion c_j belongs to the effect group and is being influenced by other criteria. Finally, map the dataset of $(R + D, R - D)$ and create the IRM. As shown on Figure 2, the IRM can be divided into four quadrants, where: (I) indicates core criteria or intertwined givers, II) contains driving or autonomous criteria, (III) indicates independent criteria or autonomous receivers, and (IV) shows us impact criteria or intertwined receivers.

2) STAGE 2

After obtaining the IRM, we now display the criteria in a hierarchical structure, if needed.

Step 6.5 (Optional): Structure the problem in a hierarchy of different levels, with goal, criteria, sub-criteria and alternatives (see Fig. 3). The criteria are hierarchy distributed according to the clusters displayed on the IRM of DEMATEL.

Step 7: Stablish pairwise comparisons judgments for criteria for l decision-makers. Let n be the number of criteria considered in the problem, the comparison matrix for each decision-maker $C^k(nxn)$ contains the comparison values between every pair of criteria. A fundamental scale of AHP (Table 3) was used to compare the criteria [60]. In a general notation, for every matrix

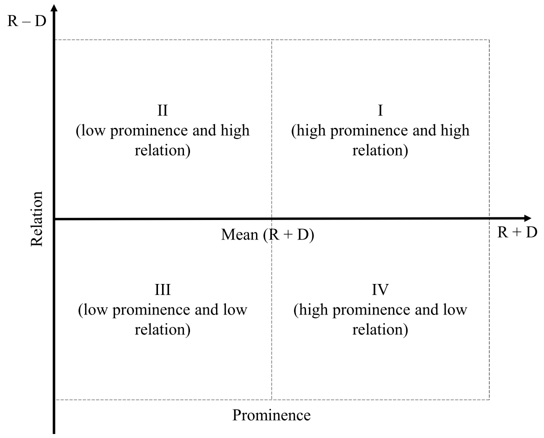

FIGURE 2. Four-quadrant IRM.

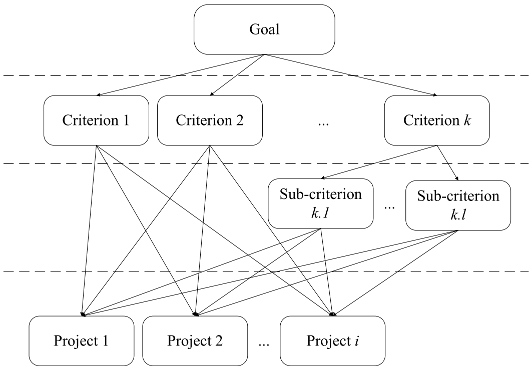

FIGURE 3. Hierarchy structure of AHP.

$$C = [c_{ij}^k] = \begin{bmatrix} c_{11}^k & c_{12}^k & \cdots & c_{1j}^k \\ c_{21}^k & c_{22}^k & \cdots & c_{2j}^k \\ \vdots & \vdots & \ddots & \vdots \\ c_{i1}^k & c_{i2}^k & \cdots & c_{ij}^k \end{bmatrix}_{mxm} \tag{15}$$

where c_{ij} = wheight of criterion i related to criterion j.

Step 8: Check the Consistency Ratio CR^k for all matrices, to make sure Decision-Makers (DM) do not make mistakes. First, obtain the normalized comparison matrices N^k for all comparison matrices C^k, where $n^k = {}^{c_{ij}}/_{\sum_{i=1}^{n} c_{ij}}$. Then, obtain the eigenvector W^{k^T} for each matrix, where $w_i^k = {}^{\sum_{j=1}^{n} n_i^k}/_{n}$.

In order to accept the estimate of each eigenvector W^k, the correspondent matrix should present a Consistency Ratio CR^k lower than 10%. The CR^k depends on the values given

$$d_i = L_D + \Delta_D \times \frac{(\tilde{d}_{i2} - L_D)(\Delta_D + \tilde{d}_{i3} - \tilde{d}_{i2})^2(U_D - \tilde{d}_{i1}) + (\tilde{d}_{i3} - L_D)^2(\Delta_D + \tilde{d}_{i2} - \tilde{d}_{i1})^2}{(\Delta_D + \tilde{d}_{i2} - \tilde{d}_{i1})(\Delta_D + \tilde{d}_{i3} - \tilde{d}_{i2})^2(U_D - \tilde{d}_{i1}) + (\tilde{d}_{i3} - L_D)(\Delta_D + \tilde{d}_{i2} - \tilde{d}_{i1})^2(\Delta_D + \tilde{d}_{i3} - \tilde{d}_{i2})} \tag{13}$$

$$r_j = L_R + \Delta_R \times \frac{(\tilde{r}_{j2} - L_R)(\Delta_R + \tilde{r}_{j3} - \tilde{r}_{j2})^2(U_R - \tilde{r}_{j1}) + (\tilde{r}_{j3} - L_R)^2(\Delta_R + \tilde{r}_{j2} - \tilde{r}_{j1})^2}{(\Delta_R + \tilde{r}_{j2} - \tilde{r}_{j1})(\Delta_R + \tilde{r}_{j3} - \tilde{r}_{j2})^2(U_R - \tilde{r}_{j1}) + (\tilde{r}_{j3} - L_R)(\Delta_R + \tilde{r}_{j2} - \tilde{r}_{j1})^2(\Delta_R + \tilde{r}_{j3} - \tilde{r}_{j2})} \tag{14}$$

TABLE 3. Scales of judgement of importance in Fuzzy AHP extent analysis.

Absolute scale	Fuzzy scale	Verbal scale	Explanation
1	(1,1,1)	Equal importance	Two criteria contribute equally to the objective
3	(2,3,4)	Moderate importance of one over another	Experience and judgement slightly favor one over another
5	(4,5,7)	Strong importance	Experience and judgement strongly favor one over another
7	(6,7,8)	Very strong importance	A criterion is very strongly favored one over another. Its dominance is demonstrated in practice
9	(9,9,9)	Extreme importance	The evidence favoring one over another is of the highest possible order of affirmation.
2, 4, 6, 8	(1,2,3), (3,4,5), (5,6,7), (7,8,9)	Intermediate importance	When needed, intermediate values between the two adjacent judgements may be used.

TABLE 4. Random consistency index *RI* for n compared criteria.

n	2	3	4	5	6	7	8
RI	0	0.58	0.9	1.12	1.24	1.32	1.41

by a Consistency Index CI^k and a Random Index RI (RI) (see, Table 4).

$$CR^k = \frac{CI^k}{RI} \tag{16}$$

where CI^k is given by $CI^k = {}^{(\lambda^k_{\max}-n)}/_{(n-1)}$, with $\lambda^k_{\max} = 1/n.\left(\sum_{i=1}^{n} z^k_i/w^k_i\right)$ and $Z^k = C^k.W^k$.

Step 9: Transform the pairwise comparison matrices C^k into a fuzzified pairwise comparison matrices $\tilde{C}^k$, according to the intensity of importance on a fuzzy scale, given by Table 3. A fuzzy membership function must be used, such as triangular membership function, where $\tilde{c}^k_{ij} = (c^k_{ij1}, c^k_{ij2}, cij3^k)$ and $\tilde{c}^k_{ji} = \left(\frac{1}{c^k_{ij3}}, \frac{1}{c^k_{ij2}}, \frac{1}{c^k_{ij1}}\right)$ if $i \neq j$.

Step 10: Aggregate de l fuzzified pairwise comparison matrices $\tilde{C}^k$ into a aggregated fuzzified pairwise comparison matrix $\tilde{C}$ by using geometric mean method.

$$\tilde{c}_{ij} = \left(\prod_{k=1}^{l} c^k_{ij}\right)^{\frac{1}{k}} = \left(c^1_{ij} \otimes c^2_{ij} \otimes \cdots \otimes c^k_{ij}\right)^{\frac{1}{k}} \tag{17}$$

Step 11: Calculate the fuzzy synthetic extent S_i with respect to i^{th} criterion.

$$\tilde{S}_i = (s_{i1}, s_{i2}, s_{i3}) = \sum_{j=1}^{n} \tilde{c}_{ij} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{n} \tilde{c}_{ij}\right]^{`-1} \tag{18}$$

Step 12: Calculate the $m(m-1)$ degrees of possibility between two criteria. In the case of criterion $c_2 = (c_{21}, c_{22}, c_{23}) \geq c_1 = (c_{11}, c_{12}, c_{13})$, the degree of possibility is obtained. Each degree of possibility measures how possible it is to a fuzzy number to dominate other.

$$V(\tilde{S}_2 \geq \tilde{S}_1) = \sup_{y \geq x} \left[\min(\mu_{\tilde{S}_1}(x), \mu_{\tilde{S}_2}(y)\right] = hgt(\tilde{S}_1 \cap \tilde{S}_2) \tag{19}$$

$$V(\tilde{S}_2 \geq \tilde{S}_1) = \begin{cases} 1, & \text{if } s_{22} \geq s_{12} \\ 0, & \text{if } s_{11} \geq s_{23} \\ \dfrac{s_{11} - s_{23}}{(s_{22} - s_{23}) - (s_{12} - s_{11})}, & \text{otherwise} \end{cases} \tag{20}$$

Step 13: Calculate the m degrees of possibility for a convex fuzzy number to be grater than $n = (m-1)$ convex fuzzy numbers.

$$V(\tilde{S} \geq \tilde{S}_1, \tilde{S}_2, \ldots, \tilde{S}_n) = \min V(\tilde{S} \geq \tilde{S}_i), i = 1, 2, \ldots, n \tag{21}$$

Step 14: Calculate the normalized importance vector $W = [w_i]_{mx1}$. First, obtain the non-normalized importance vector W', than normalize it, obtaining the normalized importance vector $W = [w_i]_{mx1}$.

$$W' = [d'(A_1), d'(A_2), \ldots, d'(A_i)]^T \tag{22}$$

$$w_i = \frac{w'_i}{\sum_{i=1}^{m} w'_i} \tag{23}$$

where $d'(A_1) = \min V(\tilde{S}_i \geq \tilde{S}_j)$, for $i, j = 1, 2, \ldots, m$ and $i \neq j$. Here w_i indicates the importance of each criterion according to the decision makers.

3) STAGE 3

Step 15: Calculate the overall weights w_0 for all criteria. According to Khazai *et al.* [58] The overall weight w_0 of each criterion is computed by correcting the importance weights w_i by its dependency weights of criteria w_d.

$$w_0 = w_i \times w_d \tag{24}$$

$$w_d = 1 - \frac{r_i - r_{\min}}{r_{\max} - r_{\min}}. \tag{25}$$

The overall weight w_0 is the output we seek, it presents a list of weights assigned to each criteria or sub-criteria according to their influence and importance over each other. As noticed in Steps 12 and 13, the values obtained for V may assume null values to unnecessary criteria. The methodology have also considered uncertainty related to data imprecision.

TABLE 5. Experts and their qualifications.

#	Experience in PPS in the organization	Experience in PPS	Higher education degree	Participation as	Organization
E1	17 years	17 years	Doctorate	Decision maker	ANEEL
E2	3 years	10 years	Doctorate	Decision maker	ANEEL
E3	3 years	5 years	Doctorate	Board Director Member (Responsible for implementing guidelines for R&D PPS)	ANEEL

C. IMPLEMENTING AND VERIFYING THE MODEL

After its formulation, the model was implemented in MS Excel® and Python. We have purposely chosen MS Excel® because it is a common and easy to use tool. It makes the approach more useful to small-sized/profitable organizations. The second reason is that choosing a popular and widespread spreadsheet software makes the model easier to be replicated by organizations that already perform R&D PPS. It would enhance the usage of structured criteria selection approaches.

First, the MS Excel® model was tested on a small set of criteria and it returned possible results. However, since it is a novel integration approach, we could not verify the spreadsheet validity by comparing it to pre-processed data. Then, in order to verify the capability of MS Excel® to return results aligned to the proposed model, we have also developed an application in Python Programming Language. Both applications, in MS Excel® and Python language returned the same results. We also made The Excel files and the Python code available here: http://bit.ly/33we3C5. In Figs. 4 and 5 we also provide an application framework, from the user's point of view.

Since one positive feature of the proposed model is the possibility to assign zero value to the final weights, it also causes an issue when only ranking a couple of criteria. When comparing just a few criteria (i.e., only three), most criteria may display overall weight zero. The extent analysis method is the main cause for this problem, since this approach works with the concept of fuzzy domination. Thus, we better explored the method when also choosing the criteria, and not only ranking a small number of already selected criteria.

Another important feature of the method is the IRM, which we present before proceeding to AHP. It seemed very useful to group the criteria, which significantly reduces the number of interactions in AHP. However, it also makes the disadvantages of classic AHP and DEMATEL to still persist in the proposed approach, for instance, the effort required to complete large matrices (usually greater than 8 compared elements, which would induce inconsistency to the data and turn laborious the data-collecting process). It is mainly noticed on the fuzzy-DEMATEL part of the method, since it does not allow hierarchy structures on traditional approaches. Some authors propose hierarchical DEMATEL approaches, which mitigates the efforts to complete large matrices. However, the approach will not be able to contemplate the grouping step we propose. [64]–[66].

Another possible question about the method concerns the usage of CFCS defuzzification approach, instead of combining all the results prior using the Extent Analysis method. In fact, this is a possible option, that would significantly reduce computational effort and also simplify the proposed model. However, since it would not generate crisp values after using AHP, we may not be able to perform the grouping stage. It is only possible if the IRM is previously displayed.

IV. DATA AND VARIABLES

Brazil has experienced increasing investments in R&D over the last years. From 2000 to 2016, the amount invested in R&D has grown more than 500%. The investment of US$ 3,3 billion in 2000 is far behind the US$ 21 billion invested in 2016. In the period, the average amount invested in R&D grew around US$ 10,3 billion. From those, US$ 5,4 billion (around 53%) comes from public sources and US$ 4,9 billion (around 47%) from corporate sources. This proportion of public and corporate investments is close to yearly averages of 52% and 48%, respectively, pointing out a parity of investment between the sectors [67]. This proportion of expenditure in R&D is not similar to those practiced by developed countries. In general, public sources in those countries spend much less capital in R&D when compared to the total invested. In 2013, for example, public capital in Germany, Japan and United States of America was respectively responsible for 29%, 17% and 28% of the total invested in R&D [68].

Among the Brazilian R&D public organizations, ANEEL (The Brazilian Electricity and Regulatory Agency) is among the most representative ones. It is an autarky founded in 1997 under a special regime and linked to Brazilian Ministry of Mines and Energy. Its purpose is to regulate the Brazilian electric sector. At the end of 2018, ANEEL approved a budget for energetic development in 2019 of US$ 5.2 billion. From 2008 to 2017, ANEEL made around US$ 1.2 billion available for financing R&D projects in the electricity sector, of which around 89% was used.

In this work, three experts from ANEEL have tested the proposed method and 18 out of 23 criteria are selected and prioritized according to their expectations. The 23 criteria were presented by the experts based on their experiences and previous project selections. How the list of 23 criteria was constructed and advanced information about previous PPS performed by ANEEL are not contemplated by our article. The experts are highly qualified and a short profile of them is summarized in Tab. 5. We present and describe the initial 23 criteria on Fig 6.

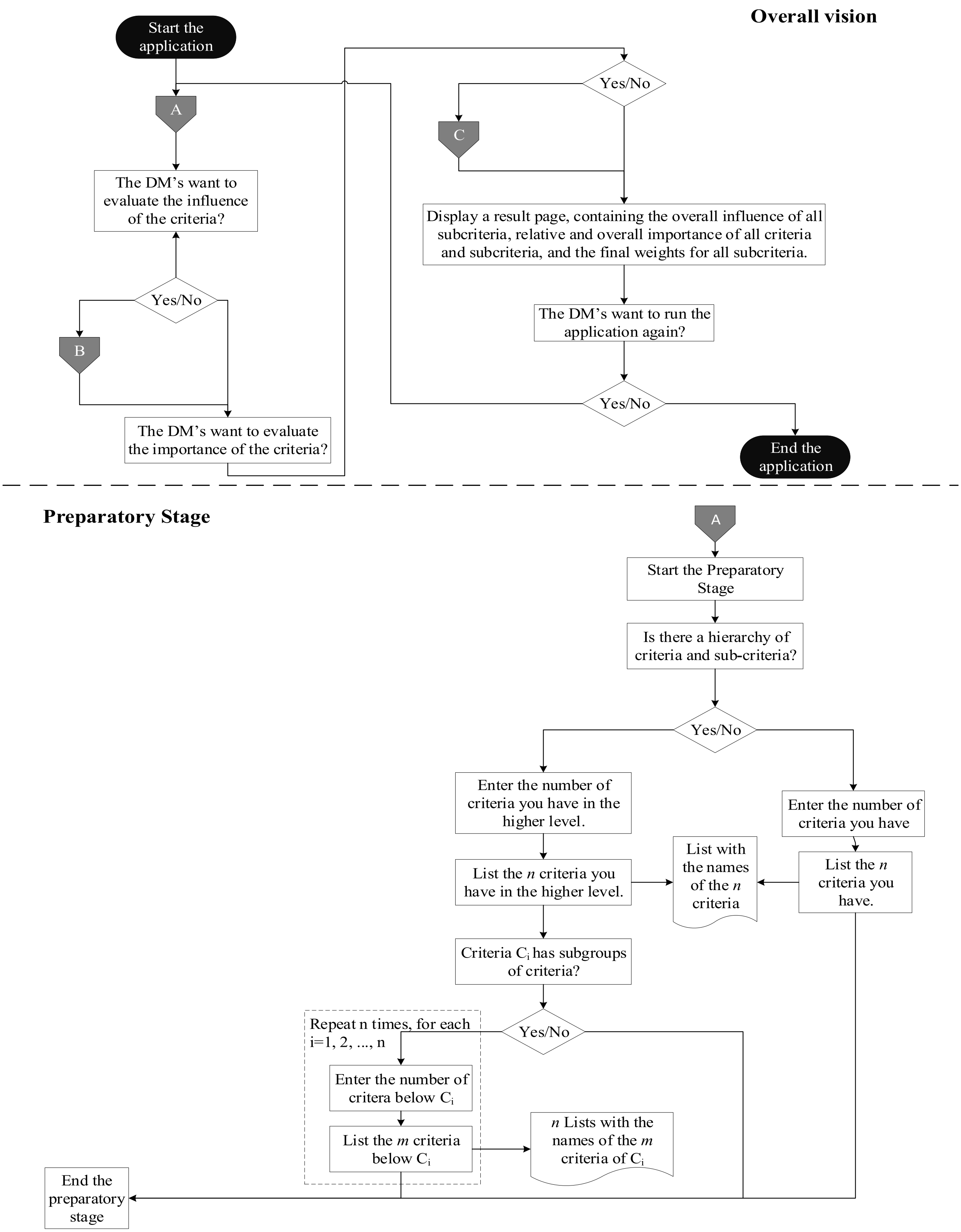

FIGURE 4. Method framework from the user point of view (a).

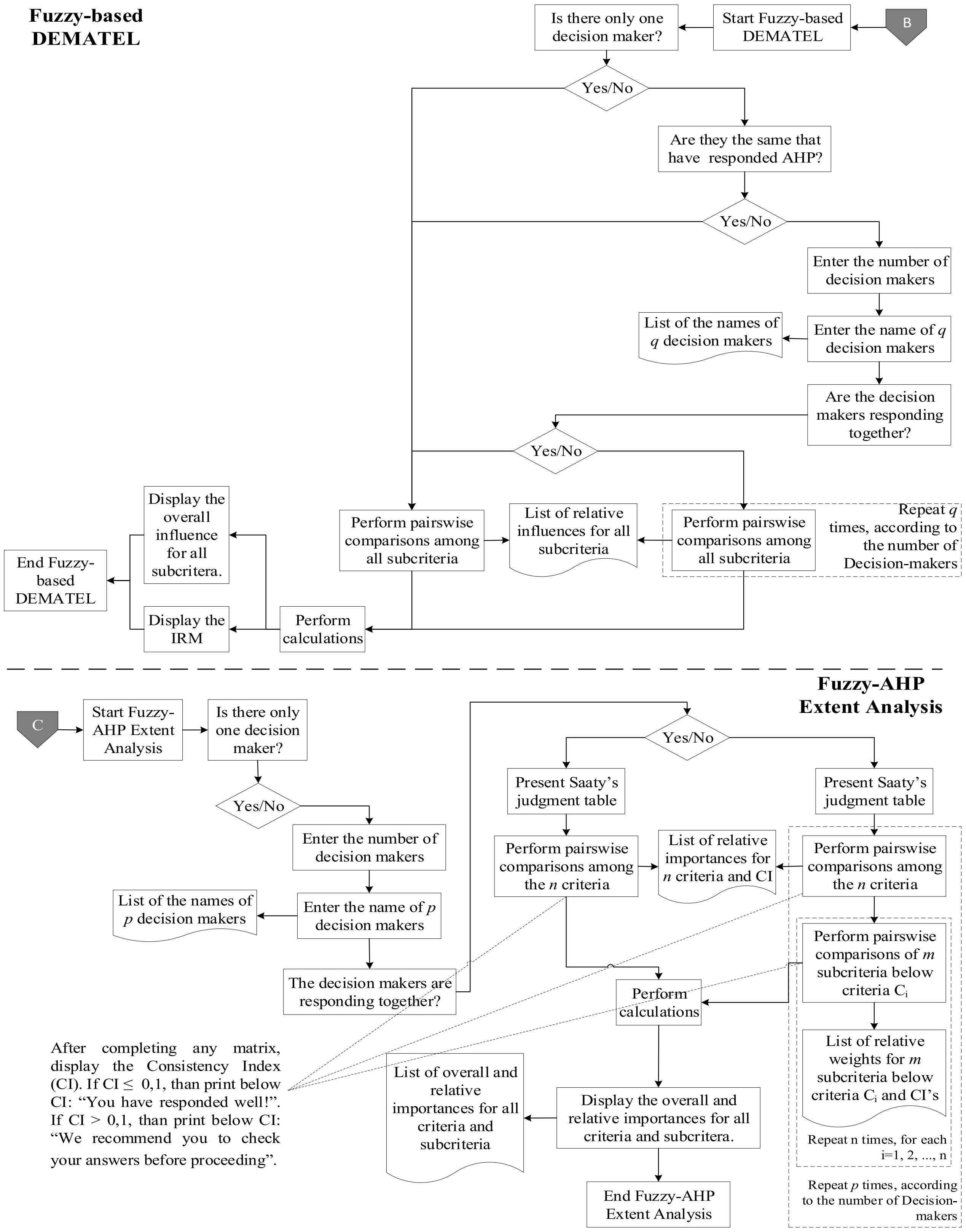

FIGURE 5. Method framework from the user point of view (b).

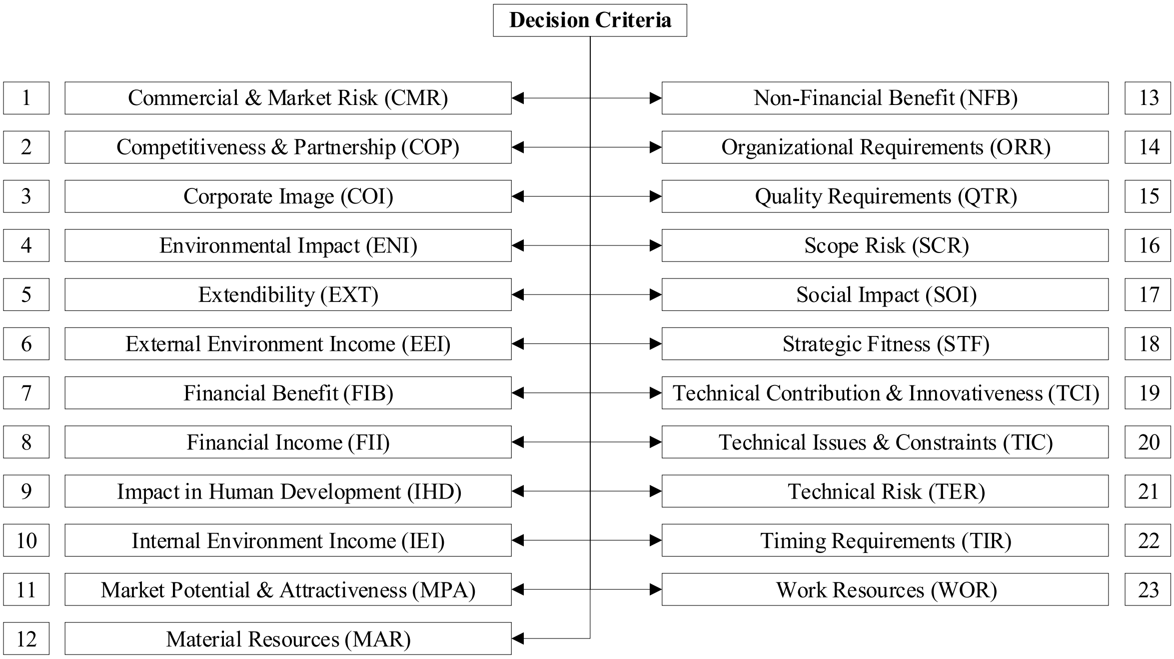

FIGURE 6. List of decision criteria that we have employed in this case.

TABLE 6. Individual direct-influence matrix for Decision-Maker 1.

	CMR	COP	COI	ENI	EII	EXT	FIB	FII	IHD	IEI	MPA	MAR	NFB	ORR	QTR	SCR	SOI	STF	TCI	TIC	TER	TIR	WOR
CMR	**0**	3	3	2	0	1	4	0	0	0	3	0	1	0	0	0	1	1	1	0	0	0	0
COP	1	**0**	4	1	0	2	3	0	1	1	4	0	2	0	0	1	1	4	1	1	2	0	1
COI	0	2	**0**	1	0	0	1	0	1	0	2	0	1	0	0	0	1	0	0	0	0	0	2
ENI	3	1	4	**0**	0	0	1	0	0	0	3	0	3	0	0	1	1	3	1	4	0	0	0
EII	3	3	2	0	**0**	0	2	3	0	1	4	1	2	1	2	3	0	0	3	3	3	3	1
EXT	2	4	3	2	0	**0**	2	0	2	0	3	0	2	0	0	1	2	2	3	1	2	0	0
FIB	4	4	4	3	0	2	**0**	1	1	0	3	0	2	0	0	4	3	3	3	1	4	0	0
FII	1	3	0	4	0	1	4	**0**	3	1	2	2	3	3	4	2	4	2	3	1	1	4	2
IHD	2	2	2	1	0	1	1	0	**0**	2	0	0	1	0	0	3	1	2	2	1	1	0	4
IEI	2	3	2	0	0	3	2	2	3	**0**	1	4	2	3	3	2	0	3	3	3	2	2	4
MPA	3	2	3	2	2	1	4	3	0	1	**0**	1	2	0	1	3	2	0	1	2	3	2	1
MAR	1	2	1	4	0	1	1	3	1	1	2	**0**	2	1	4	1	0	0	2	3	2	3	4
NFB	0	3	3	3	0	3	2	0	4	0	1	0	**0**	0	0	1	3	2	4	2	1	0	3
ORR	2	2	3	2	0	1	2	2	2	0	2	1	3	**0**	3	3	2	4	1	4	2	2	1
QTR	1	3	4	1	0	1	3	4	2	0	4	4	1	2	**0**	3	1	2	2	3	2	4	3
SCR	2	3	2	2	0	1	4	0	1	0	0	0	2	0	0	**0**	1	0	2	2	1	0	0
SOI	3	1	4	1	0	0	1	0	2	0	3	0	3	0	0	1	**0**	3	1	2	0	0	1
STF	0	3	4	1	0	1	1	0	1	0	1	0	1	1	0	0	1	**0**	2	4	0	0	1
TCI	4	2	3	4	0	4	2	0	4	0	3	0	4	1	0	4	4	1	**0**	4	4	0	0
TIC	2	3	2	1	0	3	3	0	3	0	1	1	4	1	0	2	1	3	4	**0**	3	0	1
TER	2	3	3	4	0	3	3	0	1	0	0	0	3	0	0	0	3	0	4	3	**0**	0	0
TIR	3	3	2	1	0	0	3	3	2	1	4	2	2	3	4	4	1	2	2	1	3	**0**	4
WOR	2	3	2	2	0	2	3	4	4	1	2	4	4	3	4	3	2	1	2	2	3	4	**0**

V. ANALYSIS AND RESULTS

First, the three experts have grouped the 23 criteria in a hierarchical structure. To do so, we have created the Fuzzy-based DEMATEL IRM, through steps 1 to 6 of the proposed model. Next, the experts have pointed out the influence of each criterion over all criteria. Then, we aggregated the three individual direct-influence fuzzy matrices $\tilde{C}_k$ into a group direct-influence fuzzy matrix $\tilde{C}$. To build the inner dependence fuzzy matrix $\tilde{G}$, we set a threshold α by taking the average values from the total-influence fuzzy matrix $\tilde{T}$. Then, we obtained the fuzzy dispatcher $\tilde{D}$ and receiver $\tilde{R}$ groups. Once defuzzified, they resulted in dispatcher D and receiver R groups with crisp numerical values. Tables 6, 7, and 8 contains the values of all the Individual direct-influence matrix. Notice that this matrix is the only input we need to perform the first stage of the proposed method.

TABLE 7. Individual direct-influence matrix for Decision-Maker 2.

	CMR	COP	COI	ENI	EII	EXT	FIB	FII	IHD	IEI	MPA	MAR	NFB	ORR	QTR	SCR	SOI	STF	TCI	TIC	TER	TIR	WOR
CMR	**0**	2	3	1	0	2	3	3	1	1	3	3	1	1	2	2	1	1	2	2	1	3	3
COP	2	**0**	4	2	2	1	4	1	3	2	1	2	2	2	3	3	2	2	3	3	2	3	4
COI	1	2	**0**	1	0	0	1	0	1	2	2	1	0	0	1	1	1	0	0	0	1	0	3
ENI	1	2	4	**0**	1	1	1	1	2	1	1	0	2	1	1	1	2	1	1	1	1	1	0
EII	3	4	1	1	**0**	2	3	3	2	3	3	2	3	2	4	3	1	2	4	2	3	3	3
EXT	3	1	0	2	1	**0**	2	0	2	1	2	1	1	1	1	3	1	2	2	2	3	2	1
FIB	2	3	2	1	1	1	**0**	1	2	1	1	0	1	3	2	2	1	1	1	1	2	3	0
FII	4	3	2	2	0	2	4	**0**	3	1	4	4	2	2	2	3	1	2	3	1	2	3	4
IHD	1	1	2	1	1	1	1	1	**0**	2	2	0	3	1	1	2	1	1	1	1	2	2	1
IEI	2	3	3	1	1	2	2	2	3	**0**	3	1	2	2	4	3	0	2	2	4	3	3	3
MPA	4	3	3	1	0	0	4	1	1	0	**0**	1	2	1	1	3	1	1	1	0	2	2	2
MAR	2	4	2	1	0	2	4	4	1	2	3	**0**	2	1	4	3	1	1	2	1	4	4	2
NFB	1	2	1	1	1	2	1	1	2	1	2	0	**0**	1	2	1	1	2	2	2	1	2	1
ORR	3	3	1	1	1	1	3	2	2	2	2	3	2	**0**	2	2	1	2	2	1	2	3	3
QTR	3	2	1	3	1	1	3	4	3	2	3	3	3	1	**0**	3	1	2	2	2	3	3	3
SCR	2	2	3	1	1	1	3	4	2	2	4	4	1	1	2	**0**	1	1	1	1	2	2	4
SOI	1	1	3	2	0	1	1	1	2	1	1	0	2	1	1	1	**0**	1	2	1	1	1	0
STF	2	2	1	2	1	1	1	1	2	2	2	1	1	2	3	3	1	**0**	2	2	2	2	1
TCI	2	2	4	1	1	1	3	2	2	3	3	0	2	1	2	2	1	1	**0**	2	2	3	0
TIC	1	2	0	1	1	1	2	3	1	1	3	3	1	1	2	1	1	2	2	**0**	1	2	3
TER	2	2	3	1	0	1	2	3	2	1	3	3	1	2	3	2	0	1	3	1	**0**	3	3
TIR	4	3	2	2	0	2	4	4	3	2	3	3	3	1	2	3	1	3	4	2	3	**0**	4
WOR	2	4	3	1	0	3	4	4	2	2	4	4	3	1	4	3	1	1	3	1	4	4	**0**

TABLE 8. Individual direct-influence matrix for Decision-Maker 3.

	CMR	COP	COI	ENI	EII	EXT	FIB	FII	IHD	IEI	MPA	MAR	NFB	ORR	QTR	SCR	SOI	STF	TCI	TIC	TER	TIR	WOR
CMR	**0**	2	3	1	0	1	3	1	0	0	3	1	2	0	1	1	1	1	1	1	0	1	1
COP	1	**0**	4	1	1	1	3	0	2	1	2	1	2	1	1	2	2	2	2	2	2	1	2
COI	0	2	**0**	1	0	0	1	0	1	1	2	0	0	0	0	0	1	0	0	0	0	0	2
ENI	2	1	4	**0**	0	0	1	0	1	0	2	0	2	0	0	1	2	2	1	2	0	0	0
EII	3	3	1	0	**0**	1	2	3	1	2	3	1	2	1	3	3	1	1	3	2	3	3	2
EXT	2	2	1	2	0	**0**	2	0	2	0	2	0	1	0	0	2	2	2	2	1	2	1	0
FIB	3	3	3	2	0	1	**0**	1	1	0	2	0	1	1	1	3	3	1	2	1	3	1	0
FII	2	3	1	3	0	1	4	**0**	3	1	3	3	2	2	3	2	4	1	3	1	1	3	3
IHD	1	1	2	1	0	1	1	0	**0**	2	1	0	2	0	0	2	1	1	1	1	1	1	2
IEI	2	3	2	0	0	2	2	2	3	**0**	2	2	3	2	3	2	0	2	2	3	2	2	3
MPA	3	2	3	1	1	0	4	2	0	0	**0**	1	3	0	1	3	2	0	1	1	2	2	1
MAR	1	2	1	1	0	1	2	2	1	1	2	**0**	2	1	2	1	1	0	2	2	2	3	2
NFB	1	3	3	3	1	3	2	1	4	1	3	0	0	1	3	1	3	3	4	2	1	2	3
ORR	2	2	2	1	0	1	2	2	2	1	2	2	2	**0**	2	2	2	2	1	2	2	2	2
QTR	2	2	2	2	0	1	3	4	2	1	3	3	3	1	**0**	3	1	1	2	2	2	3	3
SCR	2	2	2	1	0	1	3	2	1	1	2	2	1	0	1	**0**	1	0	1	1	1	1	2
SOI	2	1	3	1	0	0	1	0	2	0	2	0	2	0	0	1	0	1	1	1	0	0	0
STF	1	2	2	1	0	1	1	0	1	1	1	0	1	1	1	1	1	**0**	2	3	1	1	1
TCI	3	2	3	2	0	2	2	1	3	1	3	0	4	1	1	3	4	1	**0**	3	3	1	0
TIC	1	2	1	1	0	2	2	1	2	0	2	2	2	1	1	1	1	1	3	**0**	2	1	2
TER	2	2	3	1	0	1	2	0	1	0	0	0	1	0	0	0	0	0	3	1	0	0	0
TIR	3	3	2	1	0	1	3	3	2	1	3	2	2	2	3	3	1	2	3	1	3	**0**	4
WOR	2	3	2	1	0	2	3	4	3	1	3	4	4	2	4	3	2	1	2	1	3	4	**0**

Finally, the experts pointed out the clusters by considering the IRM and the relation among criteria in practice. Names were given to the clusters, according to the criteria inside. The clusters are displayed on Fig. 7 and Fig. 8.

As noticed, Groups 1, 2 and 3 are entirely composed by cause criteria, which has high influence over other criteria. According to the results, those criteria should be assigned with greater weights. Group 4 presents criteria that moderately influence and are influenced by others. Groups 5, 6, 7 and 8 contains only effect criteria, which are highly influenced by others. These criteria should receive lower weights.

Once in stage 2, the three experts have pointed the importance of one criterion over another according to the hierarchy established. For all comparison matrices we checked the consistency ratios *CR* and only those with *CR* greater than 0.1 were approved. Rejected matrices were reworked by the

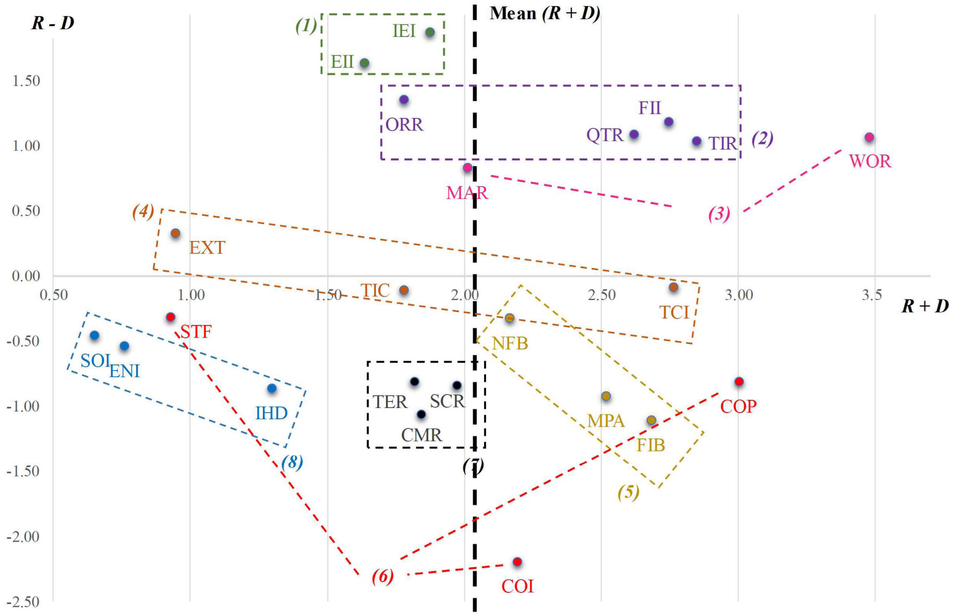

FIGURE 7. IRM Generated in Fuzzy-based DEMATEL and recommended groups of criteria.

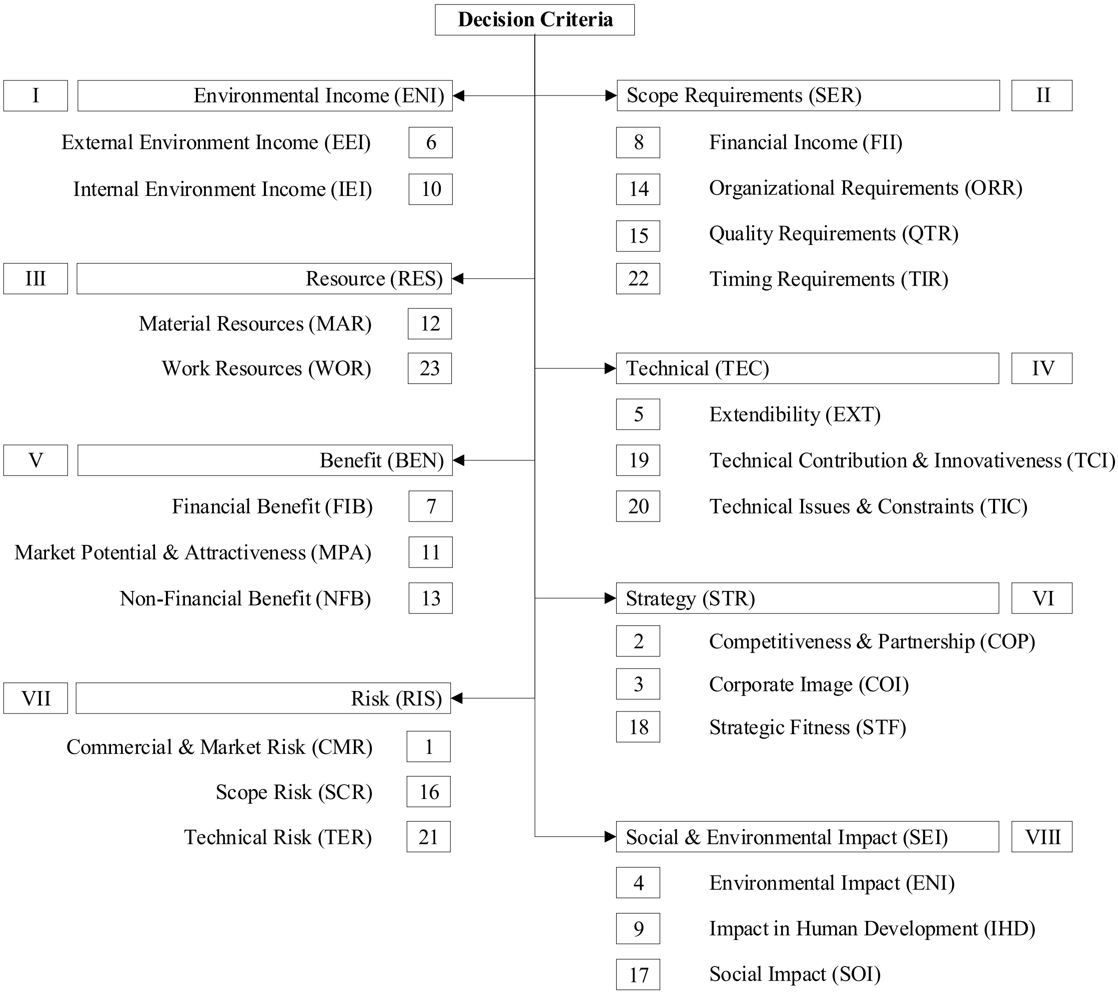

FIGURE 8. The proposed criteria hierarchical structure.

TABLE 9. AHP: Comparison matrices for Decision Maker 1.

		ENI		SRE				RES		TEC			BEM			STR			RIS			SEI			Groups									
		EEI	IEI	FII	ORR	TIR	QTR	WOR	MAR	TCI	TIC	EXT	FIB	NFB	MPA	COP	STF	COI	TER	SCR	CMR	SOI	ENI	IHD	ENI	SRE	RES	TEC	BEM	STR	RIS	SEI		
ENI	EEI	1.00	4.00																						1.0	0.5	0.5	0.3	0.5	0.3	1.0	2.0	ENI	Groups
	IEI	0.25	1.00																						2.0	1.0	1.0	0.5	2.0	0.5	1.0	4.0	SRE	
SRE	FII	CI= 0.00		1.0	4.0	3.0	5.0																		2.0	1.0	1.0	0.5	1.0	0.5	1.0	2.0	RES	
	ORR			0.3	1.0	0.5	0.5																		3.0	2.0	2.0	1.0	2.0	0.5	2.0	4.0	TEC	
	TIR			0.3	2.0	1.0	2.0																		2.0	0.5	1.0	0.5	1.0	1.0	2.0	4.0	BEM	
	QTR			0.2	2.0	0.5	1.0																		3.0	2.0	2.0	2.0	1.0	1.0	2.0	3.0	STR	
RES	WOR			CI= 0.04				1.0	3.0																1.0	1.0	1.0	0.5	0.5	0.5	1.0	2.0	RIS	
	MAR							0.3	1.0																0.5	0.3	0.5	0.3	0.3	0.3	0.5	1.0	SEI	
TEC	TCI							CI= 0.00		1.0	1.0	2.0																			CI= 0.03			
	TIC									1.0	1.0	2.0																						
	EXT									0.5	0.5	1.0																						
BEM	FIB									CI= 0.00			1.0	5.0	3.0																			
	NFB												0.2	1.0	0.3																			
	MPA												0.3	4.0	1.0																			
STR	COP												CI= 0.07			1.0	0.3	2.0																
	STF															4.0	1.0	3.0																
	COI															0.5	0.3	1.0																
RIS	TER															CI= 0.09			1.0	1.0	0.5													
	SCR																		1.0	1.0	0.5													
	CMR																		2.0	2.0	1.0	CI= 0.0												
SEI	SOI																		CI= 0.00			1.0	0.5	0.5										
	ENI																					2.0	1.0	2.0										
	IHD																					2.0	0.5	1.0										

TABLE 10. AHP: Comparison matrices for Decision Maker 2.

		ENI		SRE				RES		TEC			BEM			STR			RIS			SEI			Groups									
		EEI	IEI	FII	ORR	TIR	QTR	WOR	MAR	TCI	TIC	EXT	FIB	NFB	MPA	COP	STF	COI	TER	SCR	CMR	SOI	ENI	IHD	ENI	SRE	RES	TEC	BEM	STR	RIS	SEI		
ENI	EEI	1.00	4.00																						1.0	0.5	0.3	1.0	0.5	0.5	0.5	0.3	ENI	Groups
	IEI	0.25	1.00																						2.0	1.0	0.5	2.0	0.3	0.5	0.5	0.3	SRE	
SRE	FII	CI= 0.00		1.0	0.2	0.2	0.3																		3.0	2.0	1.0	2.0	1.0	2.0	2.0	2.0	RES	
	ORR			5.0	1.0	1.0	1.0																		1.0	0.5	0.5	1.0	1.0	2.0	2.0	1.0	TEC	
	TIR			5.0	1.0	1.0	0.3																		2.0	3.0	1.0	1.0	1.0	3.0	3.0	1.0	BEM	
	QTR			4.0	1.0	3.0	1.0																		2.0	2.0	0.5	0.5	0.3	1.0	1.0	2.0	STR	
RES	WOR			CI= 0.07				1.0	7.0																2.0	2.0	0.5	0.5	0.3	1.0	1.0	2.0	RIS	
	MAR							0.1	1.0																3.3	3.0	0.5	1.0	1.0	0.5	0.5	1.0	SEI	
TEC	TCI							CI= 0.00		1.0	7.0	3.0																			CI= 0.10			
	TIC									0.1	1.0	0.2																						
	EXT									0.3	5.0	1.0																						
BEM	FIB									CI= 0.06			1.0	1.0	0.3																			
	NFB												1.0	1.0	0.3																			
	MPA												4.0	4.0	1.0																			
STR	COP												CI= 0.00			1.0	0.3	5.0																
	STF															3.0	1.0	8.0																
	COI															0.2	0.1	1.0																
RIS	TER															CI= 0.04			1.0	3.0	1.0													
	SCR																		0.3	1.0	0.5													
	CMR																		1.0	2.0	1.0	CI= 0.0												
SEI	SOI																		CI= 0.02			1.0	0.3	1.0										
	ENI																					4.0	1.0	4.0										
	IHD																					1.0	0.3	1.0										

TABLE 11. AHP: Comparison matrices for Decision Maker 3.

		ENI		SRE				RES		TEC			BEM			STR			RIS			SEI			Groups									
		EEI	IEI	FII	ORR	TIR	QTR	WOR	MAR	TCI	TIC	EXT	FIB	NFB	MPA	COP	STF	COI	TER	SCR	CMR	SOI	ENI	IHD	ENI	SRE	RES	TEC	BEM	STR	RIS	SEI		
ENI	EEI	1.00	0.33																						1.0	0.3	0.3	0.3	0.2	0.2	0.3	0.2	ENI	Groups
	IEI	3.00	1.00																						4.0	1.0	1.0	3.0	0.5	0.3	1.0	0.5	SRE	
SRE	FII	CI= 0.00		1.0	1.0	5.0	3.0																		4.0	1.0	1.0	3.0	0.5	0.3	1.0	0.5	RES	
	ORR			1.0	1.0	5.0	3.0																		3.0	0.3	0.3	1.0	0.3	0.3	0.5	0.5	TEC	
	TIR			0.2	0.2	1.0	0.5																		5.0	2.0	2.0	4.0	1.0	1.0	2.0	1.0	BEM	
	QTR			0.3	0.3	2.0	1.0																		5.0	3.0	3.3	4.0	1.0	1.0	3.0	1.0	STR	
RES	WOR			CI= 0.00				1.0	9.0																4.0	1.0	1.0	2.0	0.5	0.3	1.0	0.5	RIS	
	MAR							0.1	1.0																5.0	2.0	2.0	2.0	1.0	1.0	2.0	1.0	SEI	
TEC	TCI							CI= 0.00		1.0	4.0	4.0																			CI= 0.03			
	TIC									0.3	1.0	1.0																						
	EXT									0.3	1.0	1.0																						
BEM	FIB									CI= 0.00			1.0	0.3	3.0																			
	NFB												3.0	1.0	5.0																			
	MPA												0.3	0.2	1.0																			
STR	COP												CI= 0.03			1.0	0.3	3.0																
	STF															4.0	1.0	8.0																
	COI															0.3	0.1	1.0																
RIS	TER															CI= 0.02			1.0	2.0	4.0													
	SCR																		0.5	1.0	3.0													
	CMR																		0.3	0.3	1.0	CI= 0.0												
SEI	SOI																		CI= 0.02			1.0	1.0	4.0										
	ENI																					1.0	1.0	4.0										
	IHD																					0.3	0.3	1.0										

TABLE 12. Values of W_i, W_d and W_o.

Acronym	Criteria	Wd	Wi	Wo
EEI	External Environment Income	1.00	1.00	14.25%
ORR	Organizational Requirements	0.90	0.92	11.77%
STF	Strategic Fitness	0.72	1.00	10.20%
ENI	Environmental Impact	0.70	1.00	10.03%
FII	Financial Income	0.64	1.00	9.18%
QTR	Quality Requirements	0.65	0.77	7.15%
WOR	Work Resources	0.45	1.00	6.41%
TER	Technical Risk	0.40	1.00	5.71%
TCI	Technical Contribution and Innovativeness	0.35	1.00	4.97%
TIR	Timing Requirements	0.59	0.47	3.96%
CMR	Commercial & Market Risk	0.34	0.63	3.04%
NFB	Non-Financial Benefit	0.43	0.48	2.96%
MPA	Market Potential & Attractiveness	0.21	0.89	2.73%
SCR	Scope Risk	0.36	0.51	2.61%
FIB	Financia Benefit	0.14	1.00	1.93%
SOI	Social Impact	0.75	0.15	1.62%
IEI	Internal Environment Income	1.00	0.10	1.38%
COP	Competitiveness & Partnership	0.13	0.04	0.07%
COI	Corporate Image	-	-	0.00%
EXT	Extendibility	0.86	-	0.00%
IHD	Impact in Human Development	0.51	-	0.00%
MAR	Material Resource	0.73	-	0.00%
TIC	Technical Issues & Constraints	0.57	-	0.00%

experts until obtaining an approved *CR*. Then, all matrices were transformed into fuzzified pairwise comparison matrices and later aggregated. The input matrices with weights given by the same three experts representing ANEEL are given by Tables 9, 10, and 11.

The Fuzzy Synthetic Extents S_i were obtained to each one of the 23 criteria and 8 groups of criteria. Then, we calculated the 562 ($23 \times 22 + 8 \times 7$) degrees of possibility, prior obtaining the 23 degrees of possibility for a convex fuzzy number to be greater than the others 22 convex fuzzy numbers. Finishing stage 2, we have obtained the weight vector W_i.

In stage 3, from fuzzy-based DEMATEL, we can obtain dependency weights of criteria w_d through. Thus, we get the Dependency Weight Vector W_d, by using inputs from the Crisp Receiver Group R.

Once we have the vectors W_i and W_d, we are able to calculate an Overall Weight Vector W_o, by multiplying the i_{th} w_i and w_d weights and normalizing the results. The set of Overall Weights w_o gives us the relative weight of one criteria over the others (see, Table 12). Criteria with greater w_o should be prioritized over those with lower w_o values.

As it can be noticed, the criteria with higher weights are those that show higher importance and higher influence over each other. If we look at the W_i column, a relevant number of criteria are assigned with full weight. It means that all of them present non-dominated fuzzy distributions. Values equal to zero represent fully-dominated fuzzy distribution. Values between 0 and 1 represent partially-dominated fuzzy numbers. On the other hand W_d presents only one zero value and only one criteria with influence 1, all other values range between those values. This difference between the set of values W_d and W_i are mainly explained by the defuzzification methods.

Qualitative criteria are the most weighted ones, such as External Environment Income, Organizational Requirements and Strategic Fitness. Quantitative criteria represent less than 30% of the total weight assigned. [69] presents four major problems in project selection. Among these problems, biased decision making (called irrational decision making by the authors) is pertinent in the context of project selection. The authors state that biased decision making reflects on selecting unnecessary projects, in order to obtain private vantages and gains over projects that could bring more economic benefit or social good. Thus, biased decision making may be observed during qualitative attribute evaluation, in which decision makers may assign higher grades to projects that give them particular advantages. Since qualitative judgments are mainly employed and knowing that the board of decision-makers is large, heterogeneous and with considerable turnover, measures should be taken to mitigate biased decision making. Possible solutions for this problem seems a gap to be explored in future R&D PPS models.

It is also important to be noticed that the criteria Environmental Impact is gaining attention of ANEEL, specially after the severe disaster occurrences on the last years, such as the Mariana and Brumadinho dam disasters, in 2015 and 2019 respectively, and the floods in Minas Gerais in 2020. The Social Impact criterion plays similar role. Although it shows great influence over other criteria, the decision-makers do not pay to it the same importance that is given to Environmental Impact criterion, yet the occurrences had also considerable social impact.

Other important results from the data is that ANEEL pays little attention to Non-Financial Benefit, such as publications and patents. The same happens to Impact in Human Development.Although the organization dictates those criteria in their documents as relevant ones, the decision-makers that select the projects seem to do not give much attention to them.

As a last fact to be notice, correlation was not explored by the proposed integrated approach, since we present no performance for the projects in each criteria. However it should be considered as a next step, prior selecting the projects. To this end, the objective MCDM methods, Criteria Importance Through Inter-criteria Correlation (CRITIC) and Coefficient and Standard Deviation (CCSD), could be explored. CRITIC, proposed by Diakoulaki *et al.* [70], assign bigger weights to criteria represented by data with lower correlation coefficient and bigger standard deviations. The correlation among criteria is used, rather then their impact on decision making. On the other hand, CCSD, proposed by Wang and Luo [71], is very similar to CRITIC, however the weight of a criteria are calculated considering the correlation between criteria and the set of scores of all alternatives, which is calculated according to Simple Additive Weighting (SAW) method. the The CCSD final step requires a non-linear model to be solved.

VI. CONCLUSION

The research presented in this work investigated the hypothesis that we can select the criteria used in R&D PPS according to their influence, importance and uncertainty. Thus, our main objective was to propose a new MCDM approach that integrates AHP and DEMATEL methods in a fuzzy environment. We conducted the whole process with the assistance of experts representing ANEEL, the main Brazilian organization of the public-electrical segment.

We have used Excel® and Python to design the method, in order to enhance its applicability in other R&D environments. The Excel® approach can be replicated and is also available online (see, http://bit.ly/33we3C5). The results from both applications, in Excel® and Python Programming Language returned the same results in all cases.

The proposed method has also shown to be applicable. It provides viable answers, based on criteria importance, influence and potential data imprecision. However some limitations were pointed out, such as: it is not recommended for decisions based on few criteria, since both fuzzy DEMATEL and AHP approaches seems to more frequently assign zero weights to the criteria, when compared to classic approaches. Thus, its recommended to use the proposed method to not only weight the criteria, but also choose them.

We can also point other delimitations of this article and proposed MADM approach: (1) the scope of this work was limited to Research and Development (R&D) Project Portfolio Selection (PPS). The proposed approach may be suitable to other fields of study inside or outside PPS; (2) the method focused only in the step of criteria selection. Other steps were not included in the scope of this work, such as decision-maker selection, project-selection and scheduling; (3) the proposed criteria selection approach is the result of integrating two well known MADM methods, AHP and DEMATEL, in a fuzzy environment. Yet the fuzzy approach we proposed seems novel in R&D PPS, similar crisp approaches may be found in other research fields; (4) the proposed approach was validated by only experts from a Brazilian public-electrical R&D organization. We expect it could be extended to other portfolios and research fields; (5) the proposed approach still present some disadvantages of individual applications of AHP and DEMATEL, such as the impossibility to take into account the aspiration level of alternatives (which are tackled by the VIKOR and TOPSIS methods, for example), the impossibility to obtain partial ranking orders of alternatives (such as ELECTRE approaches), the difficult applicability to sets of criteria that require many pairwise comparisons, and the impossibility to consider constraints (as mathematical models do).

The case of ANEEL also brings interesting conclusions. Qualitative criteria, such as External Environment Income, Strategic Fitness and criteria related to Scope Requirements are preferred, instead of traditionally considered criteria, such as Financial and Non-Financial Benefits.

Further investigations can also explore the developments, delimitation's and insights given by this work, such as the correlation between criteria. For R&D PPS applications resulting in a list of selected projects, and after collecting the inputs for all criteria and according to all analyzed projects, it is recommended to evaluate the correlation between the criteria. To this end, objective MCDM methods could be employed, such as CRITIC and CCSD, both mentioned before.

The consistency of the decision-makers was only considered when evaluating the importance of the criteria, through classic AHP. However, the measurement system could be analyzed by studies of Gage R&R, which may result in interesting findings.

The proposition of a support system to aid Brazilian public R&D organizations to select their projects may also be an idea to further research, in this case, the framework proposed by Figs. 4 and 5 could be better explored.

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