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A group MCDA method for aiding decision-making of complex problems in public sector: The case of Belo Monte Dam

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ABSTRACT

We review the applications of Multiple Criteria Decision Analysis (MCDA) methods in energy sector and in Environmental Impact Assessment (EIA), finding a gap on the non-use of specific methods that deal with divergent opinions, such as a group MCDA method. This way we suggest the application of a group MCDA method to demonstrate how it may be used for aiding group decision-making in public sector. Aiming at analyzing the aforementioned problem, we simulate the choosing of the construction alternatives of Belo Monte Dam. The power plant project was marked by several conflicts among stakeholders due to the generation of diversified environmental, social and economic impacts. The results show that a group MCDA method may be used to aid public sector in the analysis of complex problems, by dividing them into several parts, allowing, therefore, a transparent decision-making process, as well as to solve gaps in the EIA methods.

1. Introduction

Ancient thinkers, such as Aristotle, Plato and Thomas Aquinas, already pondered on human decision process. This process, approached differently through history, is recently reconsidered in studies on the Multiple Criteria Decision Analysis (MCDA) methods, which have been used to support the decision-making process [1]. On private sphere, methods such as Analytic Hierarchy Process (AHP), Elimination and Choice Expressing Reality (ELECTRE) and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) have been used as tools to improve the decision of investment portfolios in firms as well as personal investments [2]. Concerning organizations, freshly published papers deal with suppliers choosing through AHP [3–5], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [6,7], and ELECTRE [8]. On the public sphere, Canadian Federal Committee Contaminated Sites Action employed an MCDA approach [9]; British government stimulated the use of such methods in public administration through the publication of a guideline on the issue in 2000, updated in 2009 [10]; and, in Brazil, the Hydroelectric Inventory of Hydrographic Basins Manual, published by the Ministry of Mines and Energy (MME) and Electric Energy Research Center (CEPEL), applied the AHP method to one of its stages [11]. Among them, studies on group MCDA [12–16] shall be highlighted, especially those intended to build consensus and to solve the uncertainty portion generated by group application.

Together with classical methods for aiding group decision-making, including negotiation techniques, voting procedures, and game theory, such MCDA methods aim to reduce uncertainty in the decision-making process when applied to groups [17–22]. However, in voting methods, candidates are usually treated as alternatives, like a “package”, that is, each alternative is appreciated by only its label, without proper mathematical consideration of the various criteria involved in the decision. In game theory, the same phenomenon occurs, because the payoff value for choosing a strategy is usually a single value and does not present the different criteria under evaluation. On the other side, MCDA methods face difficulties in aiding group decisions because they do not take into consideration conflicts among decision makers, adopting a homogeneity principle amongst them through the use of criteria aggregation into a single group weight vector, not considering divergent opinions appropriately [23]. Mathematically saying, the aggregation procedures are applied to MCDA methods a priori, not considering the modeling of the conflict that could be solved through the method. Therefore, although MCDA methods have been used for aiding group decision-making, including i.e. the Analytical Network Process (ANP) [24], their procedures still focus on the aggregation of preferences, not on the strategic analysis of the choice of alternatives.

In this context, we may also highlight the utility function proposed in Leoneti [25], which, through a game-theoretic based approach, enables the application of a group MCDA method that strategically assesses the conflict of opinions among decision makers whitin the

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method, allowing the use of the concept of equilibrium as solution. In relation to classical methods for aiding group decision-making, Leoneti's method makes two proposals. The first proposal aims to use a multicriteria evaluation to reduce the uncertainty related to decision makers' preference over competing objectives – without preferences aggregation procedures usually performed when using MCDA methods in groups. The second proposal aims at modeling the strategic interactions of each decision maker using a utility function to choose their most preferable alternative – without the non-trivial challenge of interpersonal comparison of different decision makers' utilities, as the method performs comparisons based on each decision maker's preferences when it is necessary to swap their own choice for the offer of other players. In other words, the method presented in Leoneti [25] attempts to expand the mono-objective evaluation performed in the use of group decision procedures without the need to aggregate individual preferences, and solve this multicriteria problem in a game-theoretic environment without the need of interpersonal comparison of utilities. This justifies its choice to be presented as an example of a group MCDA method for aiding decision-making of complex problems in the public sector.

Therefore, considering the still incipient use of MCDA methods for aiding group decision-making in public sector and the recent discussions on group decision-making using MCDA methods in the context of hydropower energy sector [26–28], the general objective of the research here reported is to demonstrate how a group MCDA method may be used for aiding the decision-making of a complex problem, more specifically, the construction of Belo Monte Dam – which consists on a case involving multiple stakeholders with divergent opinions –, contributing, therefore, to public management by showing the advantages of using such techniques. Besides the aforementioned objective, we shall emphasize the problem structuring stage of the study, presenting the general problem, especially the phases of construction of the decision matrix and validation of the selected criteria through a problem structuring method (PSM) [29–31]. This paper consists of the following six sections: 2) Case Study: Belo Monte Dam, 3) MCDA methods in energy sector, 4) MCDA methods in Environmental Impact Assessment (EIA), 5) Methodology, 6) Results, 7) Discussion, and 8) Closing Remarks.

2. The Belo Monte Dam

Amazon is the world's largest rainforest that still exists [32] and it offers, as environmental services, the maintenance of biodiversity, carbon storage and water cycle conservation [33]. In Brazil, its watersheds are sources of a great potential of power energy generation not used by hydroelectric dams yet [34]. Considering that major engineering projects are options for the generation of economic development in late developing countries [35], we shall highlight the recent construction of Belo Monte Dam as an emblematic project in Brazil, as well as marked by several conflicts [36,37].

The construction of Belo Monte Dam, with 4371.78 MW of steady energy, represents an increase of about 5% to the total amount of power energy under operation in the country [34,38,39]. The conflicting themes on the construction of Belo Monte Dam refer to: (i) the influence of the hydroelectric dam complex on the economic growth of the Amazon region; (ii) the decisions made about the project; (iii) the consulted specialists on the process of choosing regarding the project; (iv) the main consumer of the generated energy; and (v) the economic feasibility of the project [40]. Protests from social movements and/or indigenous people, lawsuits and changes in energy and/or economic policy that occurred since the beginning of the project are expressions of such conflicts [36].

Among the reasons for the conflicts, there is the fact that the construction of Belo Monte Dam generates diversified impacts [41] that will cause permanent modifications on the Amazon forest biodiversity [42]. The flooding of the area of construction of the reservoir and the alteration of the flows on the Volta Grande zone of the Xingu River have already been pointed out as great environmental impacts caused by the construction of the hydroelectric dam complex [42]. Other several social and economic impacts are also present and were discussed by many studies, such as population natural movement, conduction of public hearings and forced migration of the population that inhabits the region of construction of the dam complex without proper public policies [37,43–45].

Fearnside [46] opposes to the construction of dam complexes in Amazon forest to generate power energy and to the classification of them as 'sustainable'. The author highlights that the values of the hydroelectric dam complexes in Amazon forest are overrated, while not proper attention is dedicated to social and environmental impacts along the rivers, the emission of greenhouse gases and the discussion over the destination of power energy, which will mostly supply the aluminum industry. According to the author, Brazil shall change its energy policy. We observe, therefore, that the construction of Belo Monte Dam encompasses antagonist interests among different groups, as well as contains a varied discussion over its environmental, social and economic impacts. This way, Tahseen and Karney [47], when revising the guidelines of international and financial institutions on sustainability assessment in hydropower projects, highlight the common place conflicts take in local policies. Thus, methods that aim at solving opposite opinions in a balanced manner shall be highlighted.

3. MCDA methods in energy sector

The application of MCDA methods is recurrent in the area of energy sources, especially because it encompasses the diversity of conflicts of opinion among group decision makers and easy as well as difficult measuring environmental, economic, social and technical dimensions [48]. On a recent application, Ishizaka, Siraj and Nemery [48] proposed a hybrid group MCDA method, using AHP and Geometrical Analysis for Interactive Aid (GAIA) to analyze different energy sources (gas, nuclear, solar, wind, coal, oil and tidal) for producing electricity for the next decades in the United Kingdom. The authors observed better agreement among participants concerning alternatives after the application of the method, which resulted in the preference for solar energy.

Some reviews on the energy sector shall also be highlighted. Mardani et al. [49] reviewed the application of MCDA methods to the area of energy management problems in the database Web of Science from 1995 to 2015. The authors found a variety of applied MCDA methods, especially hybrid ones. They also emphasized the publications between 2005 and 2015 with little application of group MCDA methods. Besides, the main theme of the applications was environmental impacts, and South America did not play a leading role on it. Finally, the review concluded that there is no proper attention to the construction of the decision matrix. Løken [50], reviewing different MCDA methods applied to energy planning, noticed the lack of domain in a specific method by the analysts and concluded that the choice for one method or the other is linked to the analyst's expertise.

Scott, Ho and Dey [51] reviewed, on part of their study, MCDA methods with the theme 'bioenergy resource' through the databases ScienceDirect, Emerald and ProQuest between the years 2000 and 2010. They found that major studies were those focused on the selection of different technologies, followed by policy and sustainability.

Renewable sources, especially the generation of power energy, are also commonplace to the use of MCDA methods. Ramanathan and Ganesh [52] used AHP together with Goal Programming to assess energy resources in India. Haralambopoulos and Polatidis [53] researched the consensus of a group through the application of PROMETHEE II to a case involving the choosing of renewable energy projects in Greece. Cavallaro [54] used PROMETHEE to assess concentrated solar thermal Technologies in Europe. San Cristóbal [55] used VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) in combination with AHP to evaluate different renewable energy sources to generate power energy in Spain. Catalina, Virgone and Blanco [56] used ELECTRE III to assess multi-source energy system to generate electric power in France.

MCDA methods are also used directly involving hydropower projects. Kumar and Katoch [28] used AHP to select the best sustainable installed capacity among ten different types of hydropower projects in the Himalayan region of India, demonstrating that small hydropower projects – 1–5 MW of capacity – are the most sustainable. Hunt, Bañares-Alcántara and Hanbury [27] proposed a combination of ELECTRE III and probabilistic forecasting aiming at analyzing alternatives for electricity generation in the United Kingdom.

4. MCDA methods in Environmental Impact Assessment (EIA)

Several authors revised the methods that encompass Environmental Impact Assessment (EIA) [57–60]. Since Thompson [60], which evaluated 24 different EIA methods, public participation in the analysis of different EIA methods is highlighted, as there is a need for equilibrium between the opinions of experts and society. In the review made by Thompson [60], only five methods were qualified under the criteria 'public participation' and 'group decision-making'. Besides, the use of different EIA methods altogether may display different results [61], which enhances the need for new approaches.

Decision-making theory has been applied in environmental management for decades [62], encompassing several international studies approaching MCDA methods and EIA [63–68]. MCDA, in the context of EIA, has the roles of making the decision process more transparent and improving the information received by stakeholders [69]. Janssen [69] listed several real applications of MCDA methods to the Dutch EIA context between 1992 and 2000, being Evaluation of Mixed Data (EVAMIX) and Sum Average Weight (SAW) the most used.

In Brazil, there are few and regional studies on the EIA methods used in Environmental Impact Statement (EIS). Oliveira and Moura [70], when analyzing the methods used for EIA in the EIS of the state of Ceará, in the northeast of Brazil, from 1999 to 2004 do not report on the use of MCDA methods, not even on applications of methods altogether. In their study, the most used methods were, separately, Leopold matrix and checklists. Similarly, the most used methods found by de Silva, Lustosa and Veras-dos-Santos [71] were the checklists, with no application of methods altogether nor MCDA methods. We may notice, then, that Brazil displays a scenario still underdeveloped in the use of MCDA methods in the context of EIA, what impacts on a disadvantage for public management, be it related to the proper elaboration of those documents or to the supporting of decisions i.e. that involve energy policies.

In EIA, it is necessary to consider all stakeholders (local authorities, engineers, affected population). EIA traditional methods, however, such as checklists, may not be able to encompass different opinions from different groups and need to amalgamate/aggregate them [66]. This way, Ramanathan [66] used AHP to analyze socio-economic impact assessment, which is a part of EIA, emphasizing the participation of several stakeholders on the analysis of the establishment of a liquefied petroleum gas (LGP) recovery plant. In this sense, Bottero et al. [64] also highlighted the contribution generated through the application of ANP when considering different stakeholders for deliberation and communication in a land-use plan in a small city in Italy. Bojórquez-Tapia, Sánchez-Colon and Florez [63] also emphasized the challenge of analyzing different opinions and values in the EIA context, as well as how to reach consensus among stakeholders over the environmental impact of projects. Through the case of the project of Mexico City International Airport, the authors used the AHP method to analyze two alternatives of project implementation, aiming at reaching consensus among stakeholders about the project's environmental impact.

Other studies involving MCDA methods and EIA context are also commendable. Kaya and Kahraman [65] used a fuzzy AHP-ELECTRE methodology to rank from larger to smaller the environmental impact in different urban industrial districts of Istanbul in Turkey. Sólnes [68] used AHP to analyze different alternatives of projects of industrial development in the East Coast region in Iceland, considering environmental, social and economic impacts, and suggesting the application as a tool to complement Strategic Environmental Assessment (SEA). Rikhtegar et al. [67] proposed an EIA methodology using ANP to calculate weights, and fuzzy SAW to assess the alternatives on the evaluation of environmental impact by mining projects in Iran.

There are also some Brazilian studies involving MCDA methods and EIA. Lucena [72] used ANP in a case of inter-municipal transport service, including environmental criteria. Moisa and Kaskantzis Neto [73] used AHP to evaluate the potential of environmental liabilities generation in fifteen gas stations. Lisboa and Waisman [74] used AHP to assess layout alternatives in the northern stretch of Rodoanel highway in the metropolitan region of São Paulo. The latter was the only study focusing on the EIS context.

5. Materials and methods

Once the construction of Belo Monte Dam is a complex problem divided into other several problems that need to be considered, it was initially necessary to identify which problems in the construction of the hydroelectric dam complex were mostly important – such as the reservoir size, the spillway characteristics or the turbines used. Having the major problem determined, we began the process of construction of a decision matrix for each problem through the identification of the alternatives adopted in the construction of the hydroelectric dam complex as well as optional alternatives. Then, we identified the criteria encompassing several dimensions of sustainability and techniques. Finally, after measuring the criteria for each alternative of the decision matrix, we applied the group MCDA method proposed in Leoneti [25].

We opted to use the group MCDA method proposed in Leoneti [25] because, through game theory, it assesses the conflict of opinions among decision makers without procedures of aggregation of preferences, working, therefore, differently from traditional applications of MCDA methods in the energy sector and in EIA [27,28,52–54,56,63–68]. The method circumvents this aggregation problem modeling, from the agent's preference set, the strategies that a rational decision-maker would take considering the choices of others players. It is also mentioned the fact that the method uses the concept of equilibrium as solution, which is more adherent to the situations of group decision when considering multiple objectives.

On the first stage of problem construction, we identified the main problems in Belo Monte Dam and, thenceforth, the formation of alternatives. The first part of this stage was about the exposition of six potential problems involving the construction of the hydroelectric dam complex through documental analysis of the EIS [38], the Environmental Impact Report [75] and the Basic Project of Engineering of the hydroelectric dam complex [39]. We filtered the problems, resulting into only three potential ones, and had five experts value them considering a seven-point Likert-type scale (1–7, the maximum) in agreement on the importance of the problems.[1] The experts chose two problems with higher average. The fields of expertise and area of operation of the experts that participated in this research stage are: finances; environmental impacts, sustainability and environmental law; environmental management, sustainability and decision-making; water resources, water basis and ecology; and environmental management and environmental law. Despite their expertise in the environmental area, two experts presented a significant pro-finances bias and another expert had a wide knowledge in finances. All of the experts have more than 20 years of activities in the field and, at the time we conducted this research, were professionally and/or academically involved with or

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[1] Jia, Fischer and Dyer [76] state that for group decision-making the use of ordinal variables to perform the elicitation process is convenient because of the operational difficulties of applying tradeoff methods in group environment.

Stage	Description	Data collection
1	Identification of the problems and their alternatives	Consultation to the Environmental Impact Statement, Environmental Impact Report and Belo Monte Dam Basic Project of Engineering;
		Sending of open and closed questions (Likert-type scale) questionnaires to experts;
2	Identification of environmental, social, economic and technical criteria	Consultation to the Hydroelectric Inventory of Hydrographic Basins Manual;
		Sending of Likert-type scale questionnaires and choosing of two criteria with the highest average for each dimension;
3	Validation of chosen criteria	Interview with experts and sending of open questions questionnaire (application of the qualitative part of VFT);
4	Measurement of decision matrix criteria	Interview with experts and sending of Likert-type scale questionnaire;
5	Measurement of decision makers' weights	Interview with experts and sending of questionnaire.

Chart 1. Data collection stages.

working for institutions in the state of São Paulo in Brazil, precisely public state universities, and an environmental agency. Both of the main problems were basis to the measurement of the alternatives adopted on the project, as well as the optional alternatives for each problem, that were created concerning the experts' opinion and the documental analysis previously mentioned.

On the second stage of problem construction, we identified and measured the criteria from several dimensions, process that we split into four parts. The first part was the identification of the main criteria of environmental, social, economic and technical dimensions, or, yet, of criteria that belonged to more than one dimension and that could possibly be considered in the construction of a hydroelectric dam complex. This primary identification used sixty criteria from the Hydroelectric Inventory of Hydrographic Basins Manual [11], which is already employed in the analysis of the hydroelectric use in river basins and encompasses the evolution of Brazilian knowledge on the field. On the second part, aiming at decreasing the criteria considered in the first phase, we calculated the average of the ponderation from 1 to 7 in agreement (Likert-type scale) concerning the opinion of the experts that participated in the first stage of the construction of the problem. We also chose two criteria with the highest average for each dimension, obtaining sixteen criteria. On the third part, we adapted the sixteen criteria from the previous part aiming at improving the understanding, and sketched its dimensions. On the fourth and last part, we measured the criteria adapted to each alternative of the created decision matrix to build the values of both as well as their decision matrices. Fourth part was generated from the scores presented through the application of a Likert-type scale to two experts within different fields of expertise, one in the finances field and the other in the environmental impacts, sustainability and environmental law field. In this turn, we considered the average of the scores from 1 to 9 (Likert-type scale) in each criteria. Chart 1 sumarizes the process of data collection.

On the steps that follow the construction of the problem, we applied Value-Focused Thinking [31] to validate the criteria identified. We opted to use VFT because it presents a wide range of steps when compared to other methods [30], it is used in several areas of expertise [77], and it has already been used to clarify problems in which MCDA methods were applied, working as initial step [78,79]. As we aimed at promoting the ranking identification of the objectives – fundamental, means and ends, as proposed by Keeney [31] – that may turn into criteria, we opted to apply VFT in its qualitative characteristics. This application allowed, therefore, the identification of the experts' understandings concerning the construction of a hydroelectric dam complex, and to corroborate the criteria chosen in the previous step.

We considered the number of experts enough to simulate a conflict group in the Belo Monte Dam case because they represented different areas of expertise and have different opinions, besides the fact that we did not require a statistically representative sample. To determine the weights of the decision makers, the four experts that participated on the first stage of problem construction took part again. Only the expert in environmental management and law did not participate. We measured the weights of the decision makers using a scale from 1 to 16 to the selected and adapted criteria, being 1 the greater importance. After that, we elicited the weights of the decision makers using the weight method Ranking Order Centroid – ROC [80].

Having both decision matrices of Belo Monte Dam measured and the weights of decision makers identified, we modeled a decision game as a non-cooperative[2] strategic game defined by the tuple $< \mathrm{N,A,C},\succsim_i >$, where N is the set of n players (decision makers), A is the set of m actions (alternatives), C is the set of c criteria, and $\succsim_i$ is the preference set over A for each player $i \in \mathrm{N}$. For the numeric representation of the set of preferences $\succsim_i$ jointly we used a function π: $\Re_+^{c \times n} \rightarrow [0,1]$, proposed in Leoneti [25]. This utility function shows the pay-offs for a decision game among decision makers that has three strategies: (i) maintain the initial choice; (ii) swap for the alternative proposed by an opponent; and (iii) swap for a different alternative from the alternative proposed by an opponent. The utility function for the game with two players can be seen in the equation

$$\pi(x, y) = \phi(x, IA).\ \phi(x, y).\ \phi(y, IA) \tag{1}$$

where, $\boldsymbol{x}$ is the initial alternative, $\boldsymbol{y}$ is the alternative proposed by the opponent, $\boldsymbol{IA}$ is the ideal alternative (the alternative composed with the maximum absolute values of each criteria[3]), $\phi(x, IA)$, $\phi(y, IA)$ and $\phi(x, y)$ are given by the pairwise comparison function ϕ: $\Re_+^c \rightarrow [0,1]$, according to equation

$$\phi(x, y) = \left[\frac{\alpha_{xy}}{\|y\|}\right]^{\delta}.\ \cos\theta_{xy},\ \text{where}\ \delta = \begin{cases} 1, \text{ if } \alpha_{xy} \leq \|y\| \\ -1, \text{otherwise} \end{cases} \tag{2}$$

where, $\alpha_{xy} = \|x\| \cos\theta_{xy}$ is the scalar projection of the vector $\boldsymbol{x}$ on the vector $\boldsymbol{y}$, $\cos\theta_{xy}$ is the angle between the two vectors, $\|y\| = \sqrt{y_1^2 + y_2^2 + \ldots + y_c^2}$ is the norm of the respective vector. The image of ϕ (range of the function values) varies between 0 and 1 (due to the conditional δ), meaning that the closer it is to 1 the more possible it becomes to trade the alternatives. The joint utility function for games where the number of players is more than two is given by equation

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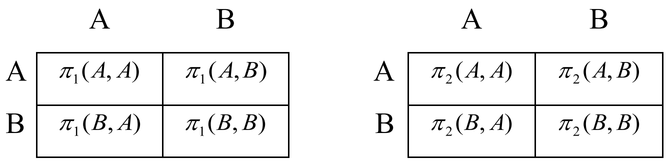
[2] It is important to mention that we use a non-cooperative approach, as we do not consider the possibility of making prior negotiations, which would allow the building of alliances for game participation. This is justified due to the characteristics of the Brazilian scenario, where agents shall not make prior agreements due to the existence of rules that aim to forbid such situation when the public sector is involved.

[3] This alternative is called 'ideal' because it contains the maximum absolute value of all criteria considered in the alternative's evaluation and, therefore, it is used as an indicator of direction to the maximum value that each criteria can eventually reach.



	A	B
A	$\pi_1(A,A)$	$\pi_1(A,B)$
B	$\pi_1(B,A)$	$\pi_1(B,B)$

	A	B
A	$\pi_2(A,A)$	$\pi_2(A,B)$
B	$\pi_2(B,A)$	$\pi_2(B,B)$

Figure 1. Framework for a game with two players and two alternatives. Source: Leoneti & de Sessa [82].

$$\pi(x, Y) = \phi(x, IA). \prod_{i=1}^{n-1} \phi(x, y_i). \phi(y_i, IA) \tag{3}$$

where $\boldsymbol{n}$ is the number of players, and $\pi(x, Y)$ defines, for a determined player, the payoff for all strategies (I, II or III) for an alternative $\boldsymbol{x}$ when trading it with another set of alternatives Y($\boldsymbol{y_i}$) proposed by all other players. The use of the joint utility function generates the payoff tables for all players, which estimates a utility measure for every possible strategy in the set of actions. Mathematically, if one of the terms (pairwise comparison function) of the utility function is close to zero, then $\pi(x, y_i)$ tends to zero, which means that only alternatives closed to IA are going to be considered in what is called "acceptable space" of the game. Therefore, a distinction between the preferable swaps will be possible and, for this reason, the matrices composed by $\phi(x, y)$ are called trade off matrices with the feature of being asymmetric. The players' likely strategies consider the fact that players might swap for alternatives that have high values given by the pairwise comparison function between the alternatives and the ideal solution. In other words, it is derived from the fact that they want to increase or at least keep their outcome in a trade.

Applying the function $\pi(x, Y)$ to each weighted performance matrix, which are weighted using the weight vector generated by the ROC method for each participant, we generate the payoffs table for all possible sets of strategies of the game (I, II or III) for each player. These payoff tables are the framework of the game translated from the original multicriteria approach. Fig. 1 presents the framework for a game with two players, two alternatives and C criteria, where $< 2, [A,B], C, \pi_i >$, that can be classified as a coordination game with players having distinct preferences according to the topology of games proposed by Robinson and Goforth [81], from which equilibrium solutions, for instance Nash equilibrium, can be calculated.

Finally, we performed sensitivity analysis to verify how stable the equilibrium solution was – in this case, Nash equilibrium – given small alterations on preference vectors.[4] In this study, we used randomly defined variations up to 50% further or less by criteria. Five hundred scenarios have been created for each problem and their results have been analyzed through descriptive statistics.

6. Results

6.1. Main problems and alternatives in the construction of Belo Monte Dam

The six potential problems involving the construction of Belo Monte Dam were (i) size of the reservoir in km^2; (ii) placement of the reservoirs; (iii) presence, absence and size of derivation channel; (iv) values of minimal low flows in m^3/s and minimal flood flows; (v) size of the dam in meters high; and (vi) project constraints. For each of those problems, there are differences in the amount of alternatives that were adopted in the construction of the project, that involve not only engineering alternatives themselves – such as turbine and turbine number – but also alternatives that reflect the engineering project and that cause social, economic and environmental impacts.

We opted to highlight the problems concerning the area of the reservoir, flows in the reduced flow stretch and places outside the complementary powerhouse. This way, we renamed the problems – then based on documental analysis – to (i) problem 1, related to the area of the reservoir; (ii) problem 2, related to the flows in the reduced flow stretch, and (iii) problem 3, related to places outside the complementary powerhouse. We chose not to work with the placement of the reservoir because it presented numerous variations on its alternatives. Instead, we used the places outside the complementary powerhouse, whose alternatives were more limited. Thus, the derivation channels and the size of the dam in meters high were not included in the analysis because they also related to the size of the reservoir. The problem 'project constraints', on the other hand, was not chosen because it presented numerous amount of alternatives.

Experts chose problems 1 and 2 as the most important ones, with averages ranging from 6.5 to 6, being 5.5 the average for problem 3. Four out of five experts measured problem 1 with maximum scoring, while problem 2 received 6 points from almost all experts – only one expert measured problem 2 with 4 points. This way, among the three highlighted problems, we considered only problems 1 and 2. Having both problems determined, we initiated the identification of the alternatives for each one of them.

The alternatives adopted in the construction of Belo Monte Dam were the 516 km^2 area of the reservoir for problem 1 and flows on the stretch of reduced flow (200 m^3/s in drought, 2,000 m^3/s during the floods, and between 1,000 m^3/s and 1,500 m^3/s during the transition period) for problem 2. We shall highlight that we obtained such values from the EIS [38] and the Basic Project of Engineering [39]. Experts were also required to identify some optional alternatives concerning the alternatives adopted in the project for problems 1 and 2. They identified the reduction in the size of the reservoir in about 30% or 40% when compared to the original project and the use of small reservoirs with small hydropower centrals (PCHs) as optional alternatives for problem 1. Concerning problem 2, the experts indicated only one optional alternative: the presence of variable flows, not permanent for specific periods.

For problem 1, alternative 1 was the alternative effectively adopted in the project of construction of the hydroelectric dam, having three optional alternatives been created, which are indicated as alternatives 1a, 1b and 1c in Chart 2. Alternatives 1a and 1b arose from the experts' opinion and alternative 1c arose from the size of the reservoir proposed in one of the first projects of the hydroelectric dam in the 1980s, when the complex was still named 'Kararaô'.[5]

For problem 2, alternative 2 was the alternative effectively adopted in the project of the construction of the hydroelectric dam, having other three optional alternatives been created, which are indicated as alternatives 2a, 2b and 2c in Chart 3. Alternative 2a arose from experts' opinion. Alternative 2b was created assuming that there might be a project that does not change the natural flows of the river. Alternative 2c presented an amount of flows that consists on the average between the natural flow of the river and the one chosen by the Project, aiming at demonstrating an intermediate alternative between alternatives 2

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[4] We considered the game as a one-shot game, not allowing new negotiation phases, what makes equilibria evolutionary analysis unfeasible.

[5] The construction of Belo Monte Dam in Amazon forest was part of the Brazilian industrialization project and started to be diagnosed in the 1970's. Eletronorte, Eletrobras subsidiary created on the same period, initiated Rio Xingu Watershed Hydroelectric Inventory Studies, mapped together with its tributaries by an engineering consortium made up of Camargo Corrêa group. After the end of the study, in the 1980's, aiming the total exploitation of the Xingu River watershed, seven dams that would generate 19,000 MW and that would represent the flooding of 18,000 km^2 were proposed, affecting 7000 indigenous besides other groups. From the seven dams, Babaquara Dams (6,600 MW) and Kararaô Dam (11,000 MW) were highlighted by Eletronorte in the 1980's, being the former initially analyzed and prioritized by the company. In the end of the 1980's, however, Kararaô Dam became the most aimed project. Given conflicts with indigenous peoples and environmentalists in 1989, the indigenous name Kararaô was changed and, in 1994, a new project was presented, reducing the flooding area from 1225 km^2 to about 400 km^2 and avoiding the flooding of the indigenous area known as Paquiçamba [83].

Identification	Alternatives	Origin
Alternative 1	Reservoir size of 516 km^2	Belo Monte Dam Basic Project of Engineering
Alternative 1a	Reservoir size of 335 km^2	Experts
Alternative 1b	Small reservoirs (presence of small PCHs)	Experts
Alternative 1c	Reservoir size of 1,225 km^2	Kararaô project in the 1980s

Chart 2. Alternatives of decision matrix 1 – Area of the reservoir.

Identification	Alternatives	Origin
Alternative 2	Flows on the stretch of reduced flows. Flows are about 200m^3/s during drought, 2,000m^3/s during flows, and between 1,000m^3/s and 1,500m^3/s during the transition period.	Belo Monte Dam Basic Project of Engineering
Alternative 2a	Variable flows, not permanent for a period	Experts
Alternative 2b	Flows closer to the natural flows of the river. The regular variation on the stretch between low and flood flows, without considering the presence of the hydroelectric dam, ranges from 1,017m^3/s to 23,414m^3/s. During the transition period, it is about 7,800m^3/s.	Project that would not change the natural flows of the river
Alternative 2c	Flows close to the natural flows. Flows are about 608.5m^3/s during drought, 4,525m^3/s during transition and 12,707m^3/s during floods.	Average between natural flows and the flows chosen by the project (Belo Monte Dam reduced flow stretch)

Chart 3. Alternatives of decision matrix 2 – Xingu River flows.

Table 1
Adapted criteria considered in the decision matrix

Code	Criteria	Direction[a]	Dimension	Total
ET1	Loss of preserved areas	Negative	Environmental	4
ET2	Pressure over terrestrial ecosystems	Negative	Environmental	
EA1	Total length of the aquatic environment to be modified	Negative	Environmental	
EA6	Impact on the quality of the water of future reservoirs	Negative	Environmental	
BE1	Affected economic production	Negative	Economic	2
BE3	Suppressed jobs and income	Negative	Economic	
MV1	Affected families	Negative	Social	4
MV3	Decline in life quality indexes	Negative	Social	
OT1	Partially and entirely affected nucleus	Negative	Social	
OT2	Rise in the need for resettlement	Negative	Social	
PIT7	Interference in the ethno-ecological conditions	Negative	Socio-environmental	2
PIT8	Impact of the flooded territory over the indigenous and traditional groups	Negative	Socio-environmental	
CTU1	Total cost of installation	Negative	Technical-economic	2
CTU4	Annual cost of operation/ maintenance	Negative	Technical-economic	
CTU2	Steady energy gain in MW	Positive	Technical	2
CTU5	Installed power in MW	Positive	Technical	

[a] For the application, all criteria were transformed into benefit criteria. Therefore, some of them were modified regarding their measurement directions.

and 2b.

6.2. *Criteria for the construction of a hydroelectric dam and their validation through VFT*

The sixteen criteria selected from the consultation to the Hydroelectric Inventory of Hydrographic Basins Manual and based on the experts' opinions are presented in Table 1.

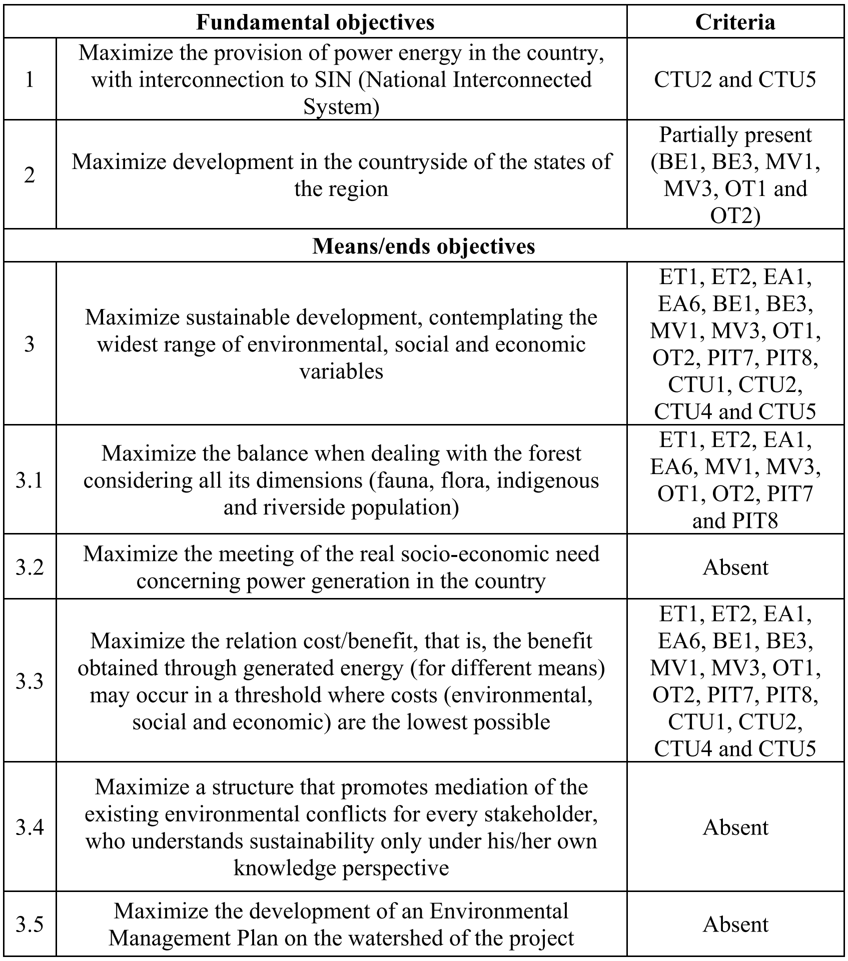
We considered all 16 criteria from Table 1 to the alternatives in problem 1 (area of the reservoir) as well as to the alternatives in problem 2 (Xingu River flows). However, before starting the measurement of the referred criteria, we validated them through the application of VFT. The objectives aimed at the construction of a hydropower dam and, specifically, at the construction of Belo Monte Dam are grouped in Chart 4, according to their types. We organized the objectives aiming at presenting a general view of the opinion of the five experts on power generation and the case of Belo Monte Dam, that is, we did not present their perspectives individually. It means that the identified objectives aimed to be easily understood.

Through the application of VFT, we verified the existence of two fundamental objectives: maximize the supply of power energy in the country and maximize development in the countryside of the states of the region. The former is clearly related to the supply of a greater amount of power energy, which is natural to expect from a hydropower dam. Concerning means and ends objectives, we found one end objective – maximize sustainable development –, which was completed by five means objectives related to: (i) dealing with the forest in a balanced way; (ii) understanding the real need for power generation in the country; (iii) promoting a proper cost/benefit relation of the project; (iv) properly mediating stakeholders; and (v) developing a suitable Environment Management Plan on the watershed of the project.

Finally, we identified that all 16 criteria from Table 1 were related to the ranked objectives (see Chart 4), what means that their selection generated assertive results concerning the construction of a hydropower dam, validating them. Thus, we may notice that all criteria were linked to an objective, although we may also notice that the selected criteria did not meet all the objectives ranked through VFT. No criterion was attached to three of the objectives and to one of them there was a partially attached criterion.

6.3. *Achieved equilibria through a group MCDA method and their evaluation through sensitivity analysis*

Table 2 displays Nash Equilibria found to the alternatives of the problem concerning the area of the reservoir in the opinion of four players. The method indicated equilibrium 3 (consensus) as the best



	Fundamental objectives	Criteria
1	Maximize the provision of power energy in the country, with interconnection to SIN (National Interconnected System)	CTU2 and CTU5
2	Maximize development in the countryside of the states of the region	Partially present (BE1, BE3, MV1, MV3, OT1 and OT2)
	Means/ends objectives	
3	Maximize sustainable development, contemplating the widest range of environmental, social and economic variables	ET1, ET2, EA1, EA6, BE1, BE3, MV1, MV3, OT1, OT2, PIT7, PIT8, CTU1, CTU2, CTU4 and CTU5
3.1	Maximize the balance when dealing with the forest considering all its dimensions (fauna, flora, indigenous and riverside population)	ET1, ET2, EA1, EA6, MV1, MV3, OT1, OT2, PIT7 and PIT8
3.2	Maximize the meeting of the real socio-economic need concerning power generation in the country	Absent
3.3	Maximize the relation cost/benefit, that is, the benefit obtained through generated energy (for different means) may occur in a threshold where costs (environmental, social and economic) are the lowest possible	ET1, ET2, EA1, EA6, BE1, BE3, MV1, MV3, OT1, OT2, PIT7, PIT8, CTU1, CTU2, CTU4 and CTU5
3.4	Maximize a structure that promotes mediation of the existing environmental conflicts for every stakeholder, who understands sustainability only under his/her own knowledge perspective	Absent
3.5	Maximize the development of an Environmental Management Plan on the watershed of the project	Absent

Chart 4. Selected objectives and criteria.

Table 2
Nash Equilibria (NE) found for problem 1 (area of the reservoir)

	Alternatives				Payoffs				Average
	Player 1	Player 2	Player 3	Player 4	Player 1	Player 2	Player 3	Player 4	
NE 1	1c	1c	1c	1c	0.266	0.079	0.069	0.009	0.106
NE 2	1	1	1	1	0.464	0.559	0.575	0.512	0.528
NE 3	**1a**	**1a**	**1a**	**1a**	**0.275**	**0.853**	**0.992**	**0.958**	**0.769**
NE 4	1b	1b	1b	1b	0.239	0.201	0.207	0.176	0.206

equilibrium[6] for alternative 1a, concerning the area of the reservoir of 335 km^2. The second best equilibrium was equilibrium 2 (consensus) for alternative 1, concerning the area of the reservoir of 516 km^2. The third and fourth best equilibria respectively involved alternatives 1b and 1c. Therefore, the alternative concerning the area of the reservoir of 335 km^2, which was not adopted in the construction of Belo Monte Dam, was assessed as the most appropriate alternative by the experts through the application of the method presented in this paper.

However, thought the highest average was for equilibrium 3, it presents strongly differences among the players' payoffs. In this equilibrium, while the majority of players would have a greater utility (represented by payoff values), player 1 would not have it if they agreed on this alternative. Therefore, 500 scenarios were created from initial preference vectors, with random variations up to 50% further or less on the weight of each criteria, to verify the stability of the solution. Among the analyzed scenarios, 472 kept the same equilibria structures presented in table 2, but 28 changed concerning equilibrium 3, which became a coalition equilibrium with player 1 adopting alternative 1. We shall observe that this represents the fact that player 1 may consider the choosing of alternative 1a unfair, what may lead to a break of agreement among players.

Nash Equilibria of the alternatives concerning the flow problem in Xingu River by the four players are listed in Table 3. The method indicated equilibrium 3 (consensus) as the best option for alternative 2b, concerning flows closer to the natural flows of the river. The second best equilibrium was equilibrium 4 (consensus) for alternative 2c, concerning flows close to the natural flows of the river, followed by equilibrium 2 (consensus for alternative 2a) and equilibrium 1 (consensus for alternative 2). Therefore, the alternative related to flows closer to the natural flows of the river was assessed as the most adequate alternative in the opinion of the experts through the application of the group MCDA method proposed by Leoneti [25], thought not

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[6] Considering the averages of the payoffs among the players, as proposed by Leoneti and Sessa [82].

Table 3
Nash Equilibria (NE) found for problem 2 (Xingu River flows)

	Alternatives				Payoffs				Average
	Player 1	Player 2	Player 3	Player 4	Player 1	Player 2	Player 3	Player 4	
NE 1	2	2	2	2	0.074	0.040	0.011	0.023	0.037
NE 2	2a	2a	2a	2a	0.291	0.223	0.176	0.148	0.209
NE 3	**2b**	**2b**	**2b**	**2b**	**0.975**	**0.976**	**0.894**	**0.977**	**0.955**
NE 4	2c	2c	2c	2c	0.664	0.849	0.885	0.927	0.831

adopted in the construction of Belo Monte Dam. This solution proved to be stable not presenting any change among the aforementioned 500 scenarios analyzed.

7. Discussion

This study emphasized the stage of problem structuring, basis to the construction of the decision matrix, in a complex case involving non-clearly defined alternatives, which is not a commonplace issue in the application of MCDA methods to solve energy problems [49]. That is, the discrimination of all parts of the decision matrix structuring provides a better understanding of the initial steps of using MCDA methods in this context. This way, it provides a better understanding of how methods can be performed in a practical way by public managers, especially those who do not have a deeper knowledge on MCDA.

On the stage of problem structuring, we identified the alternatives first and then the criteria. The order in which results were described is not attached to the choosing of a specific top-down or bottom-up approach. That is, criteria were not created through alternatives discussion – as in bottom-up approaches – nor criteria were constructed based on values/objectives that would foster the construction of new alternatives – as in top-down approaches. However, we used the ideas of top-down approaches through VFT as validation parameters.

We identified the area of the reservoir and flows in reduced flow stretch of Xingu River as the two main parts of Belo Monte Dam problem. Several authors consider both as issues of great importance and generators of several environmental impacts [41,42], validating the structuring methodology used.

Still concerning problem structuring, criteria discrimination for the assessment of hydropower dams may be considered a great contribution of this study. However, the means objectives 'maximize the meeting of a real socio-economic need of power energy generation', 'maximize a structure that promotes the mediation of environmental conflicts for each stakeholder', and 'maximize the development of an Environmental Management Plan on the watershed' were not present on the criteria listed in Table 1. They consist on gaps found for the criteria considered in the decision matrix, what demonstrates the importance of the application of VFT to foster new criteria that were not present at first. About the destination of the power energy generated by Belo Monte Dam – a gap found through the application of VFT –, several studies state that power energy generated by Belo Monte Dam will specially meet the power demands of large aluminum companies [37,41,46].

Concerning problem 1, the indicated alternative based on the preference of group members was the area of 335 km^2 of the reservoir of Belo Monte Dam, which was not a stable solution in sensitive analyses, being the area of 516 km^2 preferable in some scenarios evaluated. This occurs due to the large difference of payoff for one of the players. Both solutions, according to Fearnside [41], cannot be considered large when compared to the power energy potential of the dam complex, that is, the impacts generated by their choice are not as significant as the ones generated by larger reservoirs that produce less power energy. However, the author highlights the small amount of information spread on possible additional reservoirs to Belo Monte Dam, which will work to normalize the flow in Xingu River, increasing the power energy generation of the dam. Regarding problem 2, the indicated alternative based on the preference of group members was the alternative of 'flows closer to the natural flows of the river', which proved to be stable through sensitivity analysis. Such ranking responds to Cunha and Ferreira [42] that highlighted the impact of the flows in relation to the greater impact caused by the project, which will affect community, biome, cyclical movements of the river and seeds dispersal. Thus, the results for problem 2 are strongly related to specialized studies [41,46].

The understanding concerning Belo Monte Dam, considering the assessments of both decision matrices, was non-generalizing. This may be observed once the alternative concerning the area of the reservoir of 335 km^2, the most adequate alternative according to the group for problem 1, impairs that the flows in the Xingu River be closer to the natural ones of the river, which was the most adequate alternative in the opinion of the group for problem 2, and vice-versa.

We may note that the decisions made on the construction of Belo Monte Dam were accompanied by the EIS, the Environmental Impact Report and the Basic Project of Engineering, that is, technical documents required by Brazilian environmental law. Such studies, when properly conducted, are crucial to the decision process because they reunite several information to justify placement and technical choices concerning the alternatives adopted on the project. However, many of these documents are difficult to understand and take a long time to be analyzed by several managers involved in the decision process, as well as by population.

On the other hand, a group MCDA method may provide a faster modeling for problems in the context of EIA, promote the understanding of such problems, promote transparency to the decision process and, mainly, include several decision makers, such as those specifically affected by the construction of the project [26,63,64,66,69,72,74]. Such benefits shall be highlighted to the case of the licensing process of Belo Monte Dam, once stakeholders affected by the construction of the project were not appropriately considered [40,43].

We may suggest, therefore, that group MCDA methods may be used together with EIA methods, mainly on EIS, considering that in Brazil it is not common to find varied methods on the statements [70,71]. Specifically, group MCDA methods may be used by environmental experts when producing reports concerning EIA on the assessment stage of different alternatives of the total project or when producing commissioned environmental analysis. They may also be used by governors that produce energy public policy and that evaluate the construction of hydropower dams. This way, there may be a clear benefit for decision-making, especially in complex public policies problems, such as those involving the energy sector, as demonstrated in the Belo Monte case presented in this paper.

Finally, although there are MCDA methods applied to the context of EIA and involving decision makers with possible divergent opinions [63,64,66,69], the MCDA methods these authors use do not strategically solve the divergent opinions problem among decision makers as other MCDA methods do [25]. In the case of Belo Monte reported in this study, we solved this theoretical gap, contributing to the MCDA methods in the sense of applying them as EIA methods, which constantly deal with divergent opinions, such as hydroelectric dams construction cases.

8. Closing remarks

The main intentions of the study were: (i) apply a group MCDA method to emphasize its use for aiding the decision-making of public managers when facing complex problems – with several impacts; (ii) promote transparency through deeper discussions on complex problems; and (iii) promote the participation of stakeholders with conflicting opinions. The specific application of the group MCDA method proposed in Leoneti [25], by analyzing several impacts generated by the project and given the concept of equilibrium solution, acted in the theoretical gap of MCDA methods in energy sector and EIA methods, because they do not strategically consider different opinions of decision makers. This way, we were able to reduce uncertainty concerning the conflicting interests groups in such methods.

The modeling conducted to the use of a group MCDA method allowed a better understanding of the case, with emphasis on the two decision matrices created, listing several criteria to evaluate the hydropower dam and different construction alternatives. Other contributions intrinsically associated with the MCDA methods relate to criteria validation through a PSM method as parameter. Besides, the method was applied to a complex problem, not commonplace in studies, and we used a specific group MCDA method that strategically solves divergent opinions.

By applying a group MCDA method, we did not aim at corroborating or not the construction of Belo Monte Dam, nor to confirm or not the appropriateness of its official decision documents. In this sense, we shall recall that the MCDA approach always generates a personal outcome that is at all times related to their users.

Thus, some of the limitations of this study include all aspects related to this custom solution, such as the chosen group of experts, which may be increased in size or types of conflicts, and the chosen criteria. We shall also highlight that this study analyzed criteria and alternatives of a case at its implementation/operation stage. This way, by the time we conducted this research, real decisions had already been made and, given its complexity, the decisions encompass variables that may have evaded our control, even referring to other studies. Therefore, this study does not aim at ceasing discussions on Belo Monte Dam, but, on the contrary, at promoting them. About limitations of the group MCDA method used, we could list: (i) the calculation of Nash Equilibria, that requires the use of a software due to its complexity; and (ii) the Pairwise Comparison Function to estimate the willingness for swapping alternatives, which is modeled in linear algebra, what might present problems related to non-liner criteria.

Aiming at improving this study, we suggest future researches concerning: (i) the creation of decision matrices for other parts of the problem of Belo Monte Dam, promoting the analysis of other alternatives and the expansion of the considered criteria, (ii) the expansion of the number of decision makers, aiming at considering the people affected by the project, (iii) an analysis of the results by power energy and hydropower dam experts, (iv) the use of real/estimated values for measurable criteria, such as the operation/maintenance costs and the power rating of generated energy, and (v) the use of different pairwise comparison functions and types of equilibrium solution.

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