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ARTICLES

DECOMMISSIONING OFFSHORE OIL AND GAS PRODUCTION SYSTEMS WITH SMAA-ExpTODIM

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ABSTRACT. This study addresses the application of the Stochastic Multicriteria Acceptability Analysis (SMAA) technique, in combination with the Exponential TODIM method (ExpTODIM), by taking into consideration proposition made by Petrobras to the Brazilian National Agency for Petroleum, regarding the decommissioning of both Marlim and Voador production fields. The new approach called SMAA-ExpTODIM takes into consideration different perspectives of participants involved in decision making regarding decommissioning projects and incorporates them to its results. Besides incorporating decision makers' uncertainties and ignorance zones, this new approach explicitly considers the decision making based on the different perspectives of the Proponent and of the Regulator. The application of the SMAA-ExpTODIM approach increased robustness by adopting different probability functions for stochastic variables, for the process of formulating and modeling the decommissioning issue. This was undertaken to represent profiles associated with aversion or propensity to risks faced by institutional decision makers. For each decision maker profile, different preference structures or comfort levels are created with a choice between decision alternatives.

Keywords: Multi-Criteria Decision Analysis, SMAA, ExpTODIM, decommissioning, Oil & Gas.

1 INTRODUCTION

Decommissioning is understood as the set of activities associated with the definitive interruption of the operation of offshore oil and gas (O&G) production facilities, including the permanent abandonment and razing of wells, the removal of facilities, the proper disposal of materials, waste and tailings, and the environmental recovery of the affected region. The demand for decommissioning services is booming around the world. In the Brazilian market, the National Agency

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of Petroleum, Natural Gas and Biofuels (*Agência Nacional do Petróleo, Gás Natural e Biocombustíveis* - ANP) reveals projections for spending in the next 5 years estimated at more than 50 billion reais in decommissioning projects (ANP, 2022).

During the 1950s, marked by the beginning of intense oil exploration activity with incursions into the sea and the emergence of new techniques, the first international regulations were created for the exploration of seabed resources through the United Nations Convention on the Continental Shelf (UN, 1958), and later, the Law of the Sea (UN, 1995).

In Brazil, offshore decommissioning projects are subject to resolution No. 817 (ANP, 2020). The Brazilian Institute for the Environment and Renewable Natural Resources (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis* - IBAMA) and the Brazilian Navy are examples of governmental bodies that have great power and influence in the approval, regulation, and inspection of decommissioning activities in the national territory.

Petróleo Brasileiro S.A. (Petrobras) proposed, through the Integrated Conceptual Installation Decommissioning Program (*Programa de Descomissionamento de Instalações* - PDI) of the Marlim and Voador fields (Petrobras, 2021), decommissioning alternatives to revitalize the production of the fields. Located in the Campos sedimentary basin, with a water depth of 160 to 993 meters, about 111 km from the coast of the state of Rio de Janeiro, the Marlim and Voador fields will have their economic limits postponed through the decommissioning of 10 oil platforms, including their subsea systems and wells, and subsequent installation of two FPSO type production units (Floating, Production, Storage and Offloading).

This article uses the evaluation of five alternatives for the decommissioning of subsea systems, contemplated by flexible lines, rigid pipelines, and subsea equipment from the platforms of the Marlim and Voador fields. The institutional decision makers (DM) of the proposed problem, Petrobras, ANP, IBAMA, and the Brazilian Navy, have different incentive instruments, antagonistic and sometimes conflicting objectives. In this sense, it is relevant to develop studies to investigate the structures of preferences and value judgments in the decision-making process.

The general objective of this work is to establish an approach capable of incorporating the uncertainties of the DM zones of ignorance and the approximations of the alternatives evaluations of a complex decommissioning problem, which involves institutional DM with different incentive instruments. In other words, it seeks to establish what Aissi and Roy (2010) call "a priori robustness": an MCDA (Multiple Criteria Decision Analysis) capable of resisting criteria assessments through vague approximations and/or zones of ignorance. To this end, the combined use of the stochastic multicriteria acceptance analysis (SMAA) technique with the ExpTODIM method (Multi-criteria Interactive Decision Making in its exponential formulation) is adopted, giving rise to the SMAA-ExpTODIM approach. The new approach is then applied in the alternatives selection for the decommissioning of subsea systems from Marlim and Voador production fields.

The decision problem is evaluated from different perspectives of the main institutional DM in order to interpret zones of ignorance and profiles of risk aversion or appetite. The stochastic representation is revealed in factors internal to the MCDA proposed in the evaluation and importance of criteria weight, amplification factors, and significance of the decision problem. Extra simulations are generated by creating external factors representing points of view of conservative, neutral, and bold magnitudes of propensity, and aversion to risks representing the different perspectives of evaluation of alternatives between the Proponent (Petrobras) and Regulator (ANP, IBAMA, and the Brazilian Navy).

2 BACKGROUND

2.1 Offshore decommissioning

The decommissioning of offshore production systems is the study subject of several authors. Ekins, Vanner and Firebrace (2006) perform comparative assessments in decommissioning scenarios of offshore exploration and production structures, exploring non-financial risks versus returns. Bull and Love (2019) carry out a historical survey of alternatives and decommissioning strategies practiced in the Gulf of Mexico involving abandoning structures for coral formation. The development and study of the decommissioning of offshore systems is also a topic that has been gaining relevance among companies in the O&G sector (Petrobras, 2021; Repsol, 2017; Shell, 2017, 2020).

Being the last stage in the life cycle of an O&G exploration and production project, decommissioning must be initiated when the economic efficiency of the reservoir is lost. Kaiser (2019) states that there are two ways to extend the economic life of an asset - reduce operating costs and/or increase revenue. Whether due to external factors, such as supply, demand, price, or internal factors, as obsolescence or wear of equipment, technology, or decline in the reservoir's production factor, all can interfere with the anticipation or amendment of the economic limit of an offshore production asset.

For OGUK (2020), the full impact of the COVID-19 pandemic on commodity price volatility and demand is yet to be seen. In Brazil, throughout 2020 more than 60 O&G production platforms had their activities interrupted. In contrast, the high volatility in oil prices is due to both the resumption of world economic activity and the strong environmental pressure to reduce greenhouse gas emissions.

Different decommissioning options can be applied to the different components of an offshore production asset. The main components considered during the decommissioning process include production wells, surface facilities, and subsea facilities (Eke *et al*., 2020).

In the field of developing alternatives to decommissioning, Fowler *et al*. (2014) summarizes the options in a decision tree of total removal, partial removal, and abandonment. The decommissioning options list can be modified to suit the specific scenario, without affecting subsequent steps in the decision process (Fowler et al., 2014). Martins *et al.* (2020b) present a more detailed survey of alternatives, segregating the options between surface structure and subsea structure, ranging from the creation of wind generation units or oceanographic study stations to flexible and rigid subsea pipeline removal options.

The alternatives for decommissioning are wide, and new solutions or reuse technologies may emerge over time. Each alternative can be characterized by its own impact on the environment, costs, socioeconomic, and safety aspects, in view of the growing importance of aspects such as sustainability and environmental protection (Martins, Moraes, et al., 2020).

2.2 MCDA in offshore decommissioning

The main purpose of using MCDA methods is to provide elements to answer questions raised by a stakeholder in a decision process (Roy, 2016). DM seek help from an MCDA precisely because they have difficulty understanding which options will best meet their long-term aspirations (Belton & Stewart, 2002).

The decommissioning process is controversial, as each alternative involves different levels of costs, benefits, and risks for different groups of stakeholders and for the environment (Schroeder & Love, 2004). ANP resolution No. 817 mentions five aspects that must be considered in the preparation of the Installations Decommissioning Program, they are: Technical, Environmental, Social, Economic, and Safety. None of the criteria in isolation should be considered decisive for the definition of the alternative (ANP, 2020). These same aspects have already been considered in other evaluations and choices of alternatives to the decommissioning of an O&G production unit, both in technical reports (Repsol, 2017; Shell, 2017) and in scientific studies (Eke et al., 2020; Ekins *et al.*, 2006; Fowler *et al.*, 2014; Henrion *et al.*, 2015; Martins, Bahiense *et al.*, 2020).

2.3 Multicriteria interactive decision making with the exponential value function: the ExpTODIM method

The authors of the TODIM method (Gomes & Lima, 1991, 1992) propose the conception of Prospect Theory (Kahneman & Tversky, 1979), using a conditional function for the process of comparison by pairs of alternatives, in each evaluated criterion (Leoneti & Gomes, 2021a). Let ($A_1, A_2, ..., A_m$) be the set of m alternative solutions to the decision problem at hand and ($c_1, c_2, ..., c_n$) the set of n criteria; Gomes and Rangel (2009) highlight that experts should be asked to estimate, for each of the criteria, the contribution of each alternative to the objective associated with the criterion. Thus, an evaluation matrix ($m \ x \ n$) is composed, which still needs to be normalized. Leoneti and Gomes (2021a) evaluated several normalization techniques, having obtained the best results through linear maximization. Equation (1) is adopted when the evaluation criterion of the alternative is of the Benefit type, that is, the higher the value, the better for the decision objective.

$$P_{ij} = \frac{c_{ij}}{max c_{ij}} \tag{1}$$

Conversely, the evaluations must be normalized through equation (2) if the criterion is of the Cost type, thus obtaining the normalized matrix of alternative versus criteria.

$$P_{ij} = 1 - \frac{c_{ij}}{max c_{ij}} \tag{2}$$

The conditional function (φ_c), equation (4), uses an additive multi-attribute utility function to determine the dominance between the alternatives. Thus, let δ (A_i, A_j), equation (3), be the measure of dominance of alternative A_i over alternative A_j:

$$\delta\,(A_i,A_j) = \sum_{c=1}^{n} \varphi_c\,(A_i,A_j)\,\forall\,(i,j) \tag{3}$$

Where the exponential formulation of the TODIM method (ExpTODIM) is the one that best demonstrated adherence to the rational choice theory presented by Prospect Theory (Leoneti & Gomes, 2021a). In ExpTODIM, the additive multi-attribute conditional function (φ_c) is represented by equation (4):

$$\varphi_c(A_i,A_j) = \begin{cases} w_c(1-10^{-\rho|P_{ic}-P_{jc}|}) & if\,(P_{ic}-P_{jc})>0 \\ 0 & if\,(P_{ic}-P_{jc})=0 \\ -w_c\lambda(1-10^{-\rho|P_{ic}-P_{jc}|}) & if\,(P_{ic}-P_{jc})<0 \end{cases} \tag{4}$$

In (4) λ represents the amplitude parameter that adjusts to the different behavioral profiles of the DM in levels of loss aversion. λ is normally between 1.5 and 2.5 (Novemsky & Kahneman, 2005). $\rho \in$ N* and indicates how significant the result of the decision is for the DM (Leoneti & Gomes, 2021a). The authors suggest the adoption of a scale of favorability (Likert scale), with ρ assuming values between 1 and 5. The values assumed by ρ represent how sensitive the DM is to the decision problem. Values close to 1 reveal a bold DM with less sensitivity to losses, while values close to 5 should reflect a more conservative and risk-averse stance. Fig. 1 shows the curves for the values assumed by ρ in ExpTodim with λ = 2.25.

Once the partial dominance matrices of each criterion are obtained, it is possible through the sum of the elements of the different matrices to arrive at the final dominance matrix. This final matrix, obtained through equation (5), is the normalized measure of the global utility of each alternative.

$$\xi_i = \frac{\sum_{j=1}^{m}\delta\,(A_i,A_j) - min\sum_{j=1}^{m}\delta\,(A_i,A_j)}{max\sum_{j=1}^{m}\delta\,(A_i,A_j) - min\sum_{j=1}^{m}\delta\,(A_i,A_j)} \tag{5}$$

The global measures obtained through (5) allow the complete ordering of all alternatives. Sensitivity analyzes must be performed on λ, as well as on the weights of the criteria, on the choice of reference criterion, and on the performance evaluations of each alternative (Gomes & Rangel, 2009).

2.4 The stochastic analysis of multicriteria acceptance: the SMAA technique

SMAA is a multicriteria decision support technique for multiple DM in discrete problems. In it, DM do not need to express preferences explicitly or implicitly. SMAA has been developed in MCDA problems where criteria assessment measures are uncertain or imprecise and, for some reason, the DM preferences are unknown (Tervonen & Lahdelma, 2007).

In SMAA, the values of imprecise or uncertain criteria are represented by probability distribution functions from which the method calculates the confidence factors that describe the reliability and robustness of the analysis (Lahdelma & Salminen, 2001).

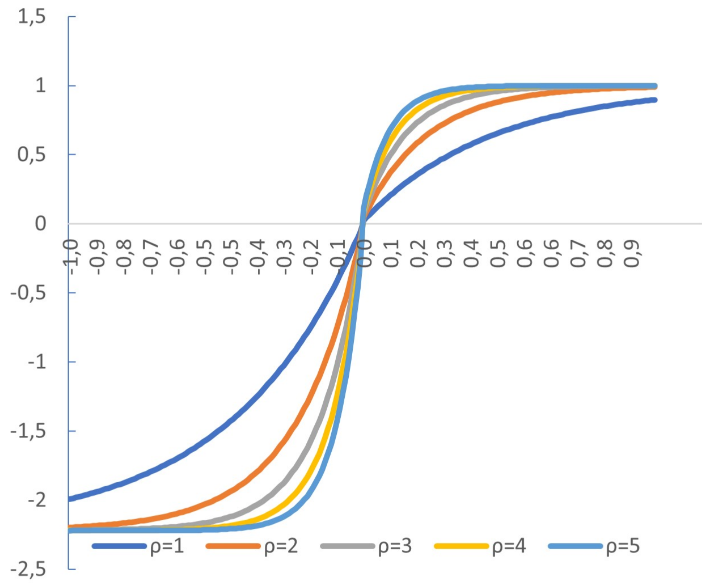

Figure 1 – Comparison of different values for the parameter ρ for the ExpTODIM function.

Decision making is performed in a real-life context that may not exactly match the model on which the MCDA is based. It is still judged in terms of a value system that will seem relevant (and not necessarily stable) to a future that may not be well defined; as a result, this value system may not exactly match the one used to create and explore the model (Aissi & Roy, 2010).

Uncertainty means that in a given situation the DM does not have quantitative and qualitatively adequate information to describe, prescribe, or predict deterministically and numerically a system, its behavior, or other characteristics. Durbach and Stewart (2012) use the term uncertainty mainly for that arising from an unknown action, which depends on future events. This is sometimes called external uncertainty because it refers to uncertainty about environmental conditions that are beyond the DM control. Internal uncertainty is related to the process of structuring and analyzing the problem. Inaccuracies in human judgments, whether of preference or weight of importance between criteria, should ideally be resolved as much as possible by better structuring the decision problem (Stewart & Durbach, 2016).

The original SMAA (Lahdelma *et al*., 1998) allows the decision analyst to measure the robustness of a decision result, through the following indices: *RAI* (Rank Acceptability Index); *CWV* (Central Weight Vector), and *CF* (Confidence Factor). There are several applications and evolutions of the SMAA methodology in the literature (Lahdelma & Salminen, 2010; Tervonen & Figueira, 2008; Tervonen & Lahdelma, 2007).

SMAA is particularly applicable in decision problems with imprecise, uncertain, or incomplete information (Tervonen & Lahdelma, 2007). The choice of the SMAA technique is due, as highlighted by Lahdelma, Hokkanen and Salminen (1998), to support multi-objective decision making for several DM. When considering the points of view of decision-makers, both Proponents and Regulators, the SMAA proves to be particularly appropriate. Ultimately, the method also allows the analysis of n-dimensional multi-objective problems with stochastic criterion values (Lahdelma *et al.*, 1998).

3 THE SMAA-EXPTODIM APPROACH

In this article, the SMAA technique is incorporated into the ExpTODIM method, obtaining what Aissi and Roy (2010) call "a priori robustness". For Aissi and Roy (2010) robustness most often involves a concern that must be considered before formulating the problem. In ExpTODIM there are four input parameters that can be simulated in the robustness evaluation, the alternative evaluation input data (c_i), the importance weights of each criterion (w_c), the amplitude parameter (λ), and the factor of significance (ρ).

The choice of the exponential formulation of the TODIM method, the ExpTODIM (Leoneti & Gomes, 2021a), is supported by incorporating the parameters of loss aversion amplitude, λ, and the significance of decision making, ρ. These parameters reinforce the possibility of adapting the MCDA to both a risk aversion or propensity profile of the decision-maker, regarding the confrontation of losses or gains, as well as the sensitivity of the DM in relation to the decision problem. These characteristics are fundamental in the representation of the different decision-makers, Proponent and Regulator, with bold, neutral, and conservative profiles, enabling the building of strategies to approach and solve the problem in an a priori robust way.

To combine the SMAA technique with the ExpTODIM method, one must simplify the ExpTODIM method to a value function where $u(i,x,q) =$ ExpTODIM (i,x,w,λ,ρ), $q = [w, \lambda, \rho]$, where $i \in M$, $M = \{1,2,...,m\}$, x is the deterministic matrix [m x n] alternative x criteria, w is the deterministic weight corresponding to the criterion, λ is the parameter of amplitude that fits the behavioral levels of the DM in loss aversion, and $\rho \in$ N* indicates how significant the decision problem is for the DM. When considering the ExpTODIM parameters λ and ρ, the following indicators are incorporated: CAF (Central Amplification Factor) and CSF (Central Signification Factor).

Let $f_{(x)}(x_{ij})$ be the PDF (probability density function) of the uncertain or imprecise evaluation of the stochastic variable x_{ij} ($\forall\ i \in M$ e $j \in N$). From the lack of knowledge, total or partial, of the preferences and attitudes of the DM to the joint probability $f_{(Q)}(q)$, the sample space Q is represented through equation (6).

$$Q = W \times \Lambda \times P = \{q = [w, \lambda, \rho] : w \varepsilon W, \lambda \in \Lambda, \rho \in P\} \tag{6}$$

Where $W \in$ R+ represents the sample space of the importance of weights, $\Lambda \in$ R | $1.5 \leq \lambda \geq 2.5$ represents the sample space of the amplitude parameter, and $P \in$ N* | $\rho \leq 5$ the sample space of the DM sensitivity in relation to the decision problem.

The probability density function $f_{(Q)}(q)$ is given by equation (7).

$$f_{(Q)}(q) = f_{(W)}(w) f_{(\Lambda)}(\lambda) f_{(P)}(\rho) \tag{7}$$

The absence of knowledge of the DM preference in the definition of importance weights between criteria allows us to consider that w assumes a uniform distribution in the W space, equation (8).

$$W = w \in R^n : w_j \geq 0, \forall j \in N, \sum_{j=1}^{n} w_j = 1 \tag{8}$$

Similarly, in a total or partial absence of knowledge of the loss aversion or propensity profile, as well as the importance that the decision problem has for the DM, uniform distributions are assumed for λ, equation (9), and ρ, equation (10), in their respective sample spaces:

$$\Lambda = \lambda \in R : 1,5 \leq \lambda \leq 2,5 \tag{9}$$

$$P = \rho \in N^* : 1 \leq \rho \leq 5 \tag{10}$$

After obtaining adequate distributions for criteria measures and preference parameters, it is necessary to derive the general utility of each alternative through stochastic simulation by simultaneous sampling of criteria measures, the criteria evaluation weights, the amplitude factor λ, and the significance factor ρ.

Tervonen and Lahdelma (2007) present the ranking of alternatives as an integer from the best classification (= 1) to the worst classification (= m) through equation (11).

$$order(i,x,q) = 1 + \sum_{j \neq i}^{m} \gamma(u(j,x,q) > u(i,x,q)) \tag{11}$$

Where γ (true) = 1, γ (false) = 0, and $u(i,x,q)$ is the utility value function ξ_i of alternative i, equation (9), obtained from the evaluation of each alternative through stochastic simulation by simultaneous sampling of criteria measures ($f_x(x)$), criteria weights (w), amplitude factor (λ), and significance (ρ) of the decision problem for the DM ρ.

Lahdelma, Hokkanen and Salminen (1998) point out that, in group decision making, DMs often have different opinions about which weights should be used for each criterion. Even a single DM may be unable or unwilling to specify weights. Thus, in SMAA-ExpTODIM, for each alternative i, the favorable preference order $Q_i^r(x)$ is determined. That is, the set of weight vectors, equation (12), makes the general utility of alternative i greater than or equal to the utility of any other.

$$Q_i^r(x) = \{q \in Q : order(i,x,q,) = r\} \tag{12}$$

From this point, the SMAA-ExpTODIM performance indexes can be defined. *RAI* is obtained by equation (13), a ratio between the expected volume of $Q_i^r(x)$ and the volume of the feasible parameter space Q.

$$RAI_i^r = \int_X f_X(x) \int_{Q_i^r} f_Q(q)\, dq dx = \int_X f_X(x) \int_{Q_i^r} f_W(w) f_\Lambda(\lambda) f_P(\rho) dw d\lambda d\rho dx \tag{13}$$

$RAI_i^r(x)$ measures the variety of different preference parameters that give A_i the ranking *r*. *RAI* assumes values between 0 and 1, with 0 being the index value of the alternative that never obtains maximum ranking for r = 1. At the other extreme, the value 1 indicates that the alternative leads the ranking for any preference parameter (Tervonen & Lahdelma, 2007; Zhang *et al.*, 2017). Based on the *RAI* obtained, one can analyze the robustness of each alternative for a given post. Robust alternatives are those with a high acceptance rate for the best ratings (Zhang et al., 2017).

The next indicator, *CWV*, is the center of gravity of the weight vector that favors the first order of alternative A_i. In SMAA-ExpTODIM it is defined by equation (14).

$$CWV_i^c(x) = \frac{1}{RAI_i^1} \int_X f_X(x) \int_{Q_i^r} f_W(w)\, dw \tag{14}$$

By definition, *CWV* will only exist for alternatives that have an acceptability index RAI_i^1 greater than 0. Analogously, the indicators *CAF* and *CSF* can be represented through equations (15) and (16).

$$CAF_i^c(x) = \frac{1}{RAI_i^1} \int_X f_X(x) \int_{Q_i^r} f_\Lambda(\lambda) d\lambda \tag{15}$$

$$CSF_i^c = \frac{1}{RAI_i^1} \int_X f_X(x) \int_{Q_i^r} f_P(\rho) d\rho \tag{16}$$

Analogously, the indicators CAF_i^c and CSF_i^c will only exist for alternatives that have an acceptability index $RAI_i^1 > 0$. The fifth indicator *CF*, equation (17), describes the probability of alternative A_i obtaining the first ranking in the ranking for a given vector of criteria weights (w), amplitude factor (λ), and significance of the decision problem for the DM (ρ).

$$CF_i^c = \int_{x \in X : order\left(i, x, CWV_i^c CAF_i^c CSF_i^c\right) = 1} f_X(x) d(x) \tag{17}$$

As it originates on bases derived from *CWV*, *CAF* and *CSF*, CF_i^c is only calculated for alternatives that have an acceptability index $RAI_i^1 \neq 0$. Confidence factors assess the measurement accuracy of criteria to robustly distinguish alternatives.

The last indicator of the SMAA-ExpTODIM is *PWI*, whose definition refers to the probability that the alternative A_i is preferred over A_j. The indicator can be represented in equation (18).

$$PWI_{ij} = \int_{[w,\lambda,\rho] \in W} \Lambda P : order(i,x,q) < order(j,x,q)\, f_W(w)\, f_\Lambda(\lambda)\, f_P(\rho) \int_X f_X(x) d(x)\, d(w)\, d(\lambda)\, (d\rho) \tag{18}$$

It is important to note that approximations due to simplifications, imperfect determinations, or arbitrary choices are not uncertain, nor are they zones of ignorance, but rather mean imperfect knowledge about the complexity of phenomena or value systems concerning the decision problem (Aissi & Roy, 2010).

Figure 2 presents the reference framework for the application of the SMAA-ExpTODIM.

The application of SMAA-ExpTODIM takes place through The Decision Tools Suite® software, a Microsoft Excel® supplement that performs Monte Carlo simulations. Practical applications of SMAA methods use a number of iterations, normally between 10^4 and 10^6 (Tervonen & Lahdelma, 2007). In the present study, we chose to perform simulations with 10^4 iterations.

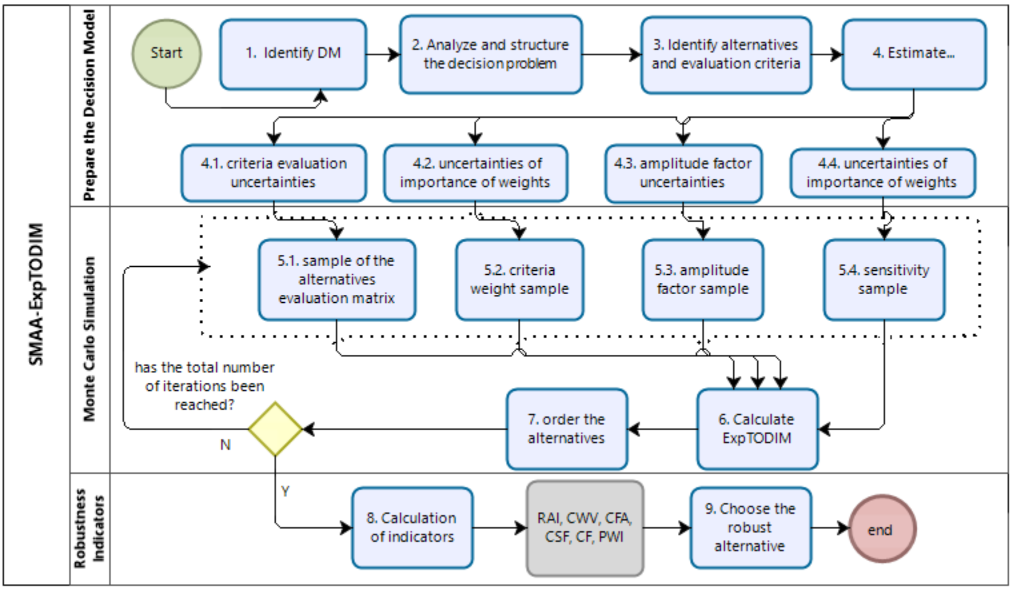

Figure 2 – Reference framework for the application of the SMAA-ExpTODIM.

4 SELECTION OF ALTERNATIVES FOR THE DECOMMISSIONING OF OFFSHORE OIL AND GAS PRODUCTION: AN APPLICATION OF SMAA-EXPTODIM

The deterministic data adopted in this study come from the report Conceptual Program for Decommissioning of Maritime Facilities for the Production Systems of the Marlim and Voador Fields (Petrobras, 2021), prepared by the Proponent Petrobras and submitted for consideration and approval by the Regulators ANP, IBAMA, and the Brazilian Navy.

Technical meetings are held with senior engineers and consultants working in the area of offshore decommissioning of O&G systems in order to identify uncertainties, their maximum and minimum limits, zones of ignorance, complexity of the decision problem, and define and typify the evaluation criteria alternatives for the decommissioning of the subsea systems of the Marlim and Voador fields. The technical meetings have pre-established agendas and seek consensus in the definition of stochastic parameters and types of criteria for the decision problem, both from the perspective of the Proponent and the Regulator.

The objective is to evaluate the real problem of selecting one of the five alternatives for the decommissioning of subsea systems (flexible lines, rigid pipelines, and equipment) of the platforms that will be decommissioned in the Marlim and Voador fields.

4.1 The Marlim and Voador fields

The PDI (Petrobras, 2021) proposes to the regulatory institutions ANP, IBAMA, and the Brazilian Navy the decommissioning of ten production platforms, including the subsea wells and associated systems. Located approximately 111 kilometers off the coast of the state of Rio de Janeiro, the decommissioning of the facilities in the Marlim and Voador fields will allow the revitalization of the fields through the subsequent installation of two FPSO type units to replace the platforms and their production systems (subsea wells and lines/equipment) that are being decommissioned.

In this study, we chose to use the evaluation data of five alternatives for decommissioning flowlines. The choice is due to the greater complexity of the subject, mainly due to the large number and variety of flexible lines installed, as well as the extension of the Marlim and Voador fields, and the diversity of existing environmental scenarios, with the recurrent presence of sensitive environments (Petrobras, 2021). In summary, the PDI presents the following alternatives:

- A_1: Full removal of flowlines after temporary deposition of risers on the seabed.
- A_2: Removal of all risers at the time of pull out and later, full removal of flowline sections.
- A_3: Platforms in “more environmentally sensitive areas”: removal of risers at the time of pull out and permanent *in situ* flowlines. For platforms in “less environmentally sensitive areas”: full removal of flexible lines after temporary deposition of risers on the seabed.
- A_4: Removal of all risers at the time of pull out and definitive in situ permanence of all flowlines, regardless of region.
- A_5: Deposition of risers on the seabed and definitive in situ permanence of all flowlines.

4.2 Application of SMAA-ExpTODIM in decision modeling

In the present study, the application of the SMAA-ExpTODIM is conducted during the selection of alternatives, the conceptual phase of a project. Therefore, records of the evaluations, criteria, and alternatives analyzed must be available to the DM, Proponent and Regulator, until the decision is taken.

Keeney and Raiffa (1993) state that in an objective there are three characteristics: a decision context, an object, and a preference direction. The context and object of decision are described in the PDI (Petrobras, 2021). Steps 1 and 2 of the SMAA-ExpTODIM implementation reference framework, Fig. 2, are already covered in the Conceptual PDI of Marlim and Voador, as well as the identification of alternatives, step 3. To identify the evaluation criteria of the alternatives, the table of quantities of operations and materials that will be applied in the decommissioning of flexible lines is selected (Petrobras, 2021). The table of quantities of operations and materials is related to the aspects presented in section 2.2. The environmental aspect is included in criteria 1, 2, 9 and 10. Safety is included in criteria 3, 4, 5, 11 and 12. The Technical, Cost and Social aspects are included, respectively, in criteria 7, 8 and 13, see Table 1.

For Figueira *et al.* (2009) a family of coherent criteria should be defined in order to reduce dependencies between criteria as much as possible. Thus, meetings were held with specialists in offshore decommissioning operations aiming to verify correlation and interdependence between criteria. It was identified that the items "quantities of risers and flowlines collected" and "quantities of risers and flowlines that will remain *in situ*" evaluate alternatives to decommissioning in an inverse, but redundant way in the same parameter, one being a Benefit type formulation and the other a Cost-type formulation. Similar characteristics are observed in the amounts of metallic materials and polymers. Another eliminated redundancy was the total operating time, given that it represents a significant portion of the cost composition of the alternatives.

After eliminating the redundancies, the group of specialists identified that one of the five criteria provided for in ANP resolution No. 817, the social criterion, was not covered. Through the collection of expert opinions, it was concluded that it was appropriate to insert the sub-criterion "employment generation", aggregating all relevant social aspects that could be evaluated at the time of proposing the PDI.

After making the adjustments to the evaluation criteria, the remaining items can be adopted in SMAA-ExpTODIM. Finally, Table 1 consolidates the quantitative evaluation criteria of the alternatives considered in the SMAA-ExpTODIM calculations.

Table 1 – Evaluation criteria for alternatives to the decommissioning of flexible lines in the Marlim and Voador fields.

Evaluation Criteria	Criterion Type		A_1	A_2	A_3	A_4	A_5
	Proponent	Regulator					
C_1 - lines collected	Cost	Benefit	1,231	725	796	435	0
C_2 - materials collected (t)	Cost	Benefit	58,569	58,569	34,450	20,840	0
C_3 - land-based lifts	Cost	Benefit	252,509	252,509	148,029	90,071	0
C_4 - heavy lifts	Cost	Cost	820	820	523	322	322
C_5 - in boardings	Cost	Benefit	498	498	422	322	0
C_6 - movements of lines over banks	Cost	Cost	1,947	1,947	463	353	0
C_7 - vessel time (days)	Cost	Benefit	3,390	4,521	3,511	3,475	1,775
C_8 - relative cost	Cost	Cost	2.1	2.2	1.7	1.1	1
C_9 - quantity of vessel trips	Cost	Cost	85	185	133	153	38
C_{10} - truck trips	Cost	Benefit	2,525	2,525	1,480	901	0
C_{11} - helicopter trips	Cost	Cost	200	180	143	110	89
C_{12} - diving operations	Cost	Cost	322	109	180	109	322
C_{13} - Relative Employment Generation	Benefit	Benefit	0.74	1	0.77	0.76	0.39

From the perspective of Petrobras evaluation, the Proponent's view, criteria C_1 to C_{12} are modeled as Cost-type criteria, that is, the lower the value, the better for the decision objective. Cost-type criteria must be normalized through equation (2). Still from the Proponent perspective, only criterion C_{13} is of the Benefit type and must be normalized as defined in equation (1). The Conceptual PDI shows the preference for an alternative that results in less environmental interference, less impact on the underwater life developed in the region, as well as a lower emission of greenhouse gases with less release of consumed energy. Furthermore, reading the PDI in conjunction with the strategic plan (Petrobras, 2020b) shows the recognition of the value of lower exposure of human life to operational risks and the preservation of natural and financial resources.

In contrast, when evaluating the approach to the decision problem from the Regulator's perspective, it is assumed that only criteria C_4, C_6, C_8, C_9, C_{11}, and C_{12} are of the Cost type. The point of view is reinforced by the opinion of the experts consulted in the elimination of redundancy in the criteria. The other criteria, C_1, C_2, C_3, C_5, C_7, C_{10} and C_{13}, are of the Benefit type.

The fourth step of the frame of reference, Fig. 2, provides for the identification of the uncertainties involved in the evaluation of the criteria (4.1), in the importance of the weights (4.2), in the loss aversion amplitude factor (4.3), and in the level of significance of the decision problem (4.4).

For the criteria evaluation uncertainties, step 4.1, the ranges of estimation variation by project maturity level of the AACE (Association for the Advancement of Cost Engineering) guideline 18R-97 are adopted (Dysert, 2016). In the variation of importance of the evaluation weights of the criteria, step 4.2 of the reference frame Fig. 2, normal PDF are adopted with a standard deviation of 10 % of the nominal weight attributed to each criterion. Fig. 3 exemplifies the stochastic function attributed to the criteria of the Security category.

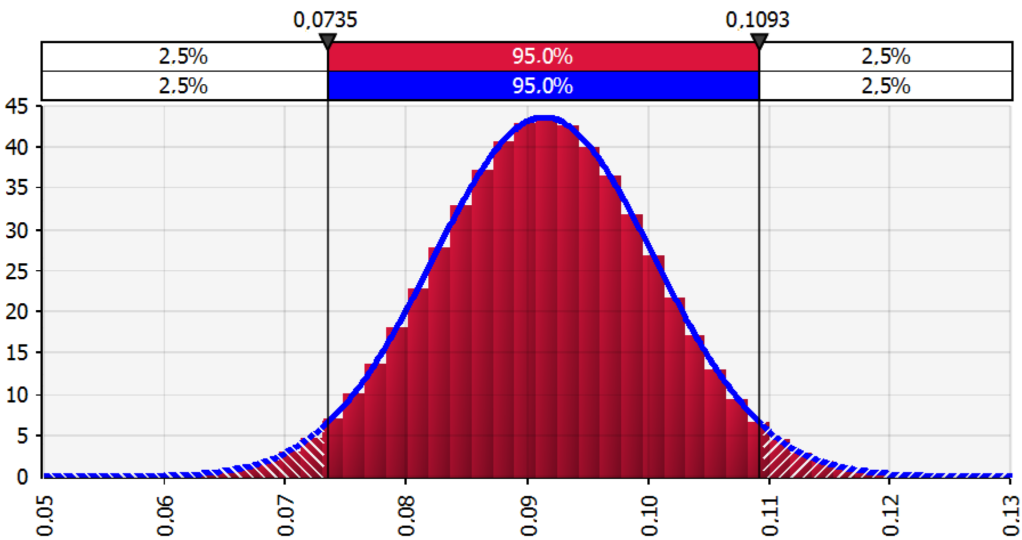

Figure 3 – Probability density function of the Security category criteria.

To define the amplitude factor, step 4.3 of the frame of reference, Fig. 2, continuous values between 1.5 and 2.5 are assigned (Novemsky & Kahneman, 2005) through a PERT function. Step 4.4 of the reference framework provides for the definition of uncertainties about the DM sensitivity to the problem. The possibility is assumed for the DM to assume one of the bold, neutral, or conservative profiles. For each profile a discrete PDF is assigned, with different pertinence for each value of the parameter ρ, according to Table 2.

4.3 Monte Carlo simulation in SMAA-ExpTODIM

The start of steps 5.1, 5.2, 5.3, and 5.4, Fig. 2, takes place with the definition of how many K iterations the Monte Carlo method will perform the SMAA-ExpTODIM calculations. The

Table 2 – PDF for DM sensitivity.

Risk profile	*Discrete function*				
	ρ=*1*	ρ=*2*	ρ=*3*	ρ=*4*	ρ=*5*
Bold	60%	20%	10%	10%	0%
Neutral	20%	20%	20%	20%	20%
Conservative	0%	10%	10%	20%	60%

number of 10^4 iterations was selected for the Monte Carlo simulations using @Risk, a Microsoft Excel® supplement, a component of The DecisionTools Suite® software.

At each k iteration, the following steps are executed:

5.1. drawing of a sample from the evaluation matrix of alternatives (x_i^k).

5.2. drawing of a sample from the possible arrangement of w_k weights for evaluating the criteria.

5.3. drawing of a value for the amplitude factor λ.

5.4. drawing of a value from the PDF of the DM sensitivity ρ, Table 2.

6. calculation of the global utility function of each alternative in ExpTODIM, ξ_i^k equation (5).

7. ordering of alternatives.

The above steps are repeated until the k iteration reaches the defined K value.

4.4 Robustness measures in SMAA-ExpTODIM

After performing the iterations of the Monte Carlo method, step 8 is implemented with calculation of the *RAI*, *CWV*, *CAF*, *CSF*, *CF,* and *PWI* indicators for each alternative, to finally choose the most robust alternative.

We chose to evaluate the decision problem from two perspectives, the point of view of the PDI Proponent (Petrobras, 2021) and the Regulatory bodies ANP, IBAMA, and the Brazilian Navy. Different risk propensity profiles on the part of the DM are also added to the PDF of parameter ρ, Table 2.

Equation (13) is applied in order to obtain the ordering acceptability index $RAI_i^r(x)$. Table 3 consolidates the acceptability results in all the ranking positions of the alternatives, for the bold, neutral and conservative risk profiles, as well as for the perspectives of the Regulatory and Proponent bodies of the decision problem.

From the *RAI* it is possible to get to the other indicators. It is through equation (14) that the central weight vector $CWV_i^c(x)$ is calculated, a weight vector that favors the positioning of the respective alternative in the first position of the order, from the perspective of evaluating the decision problem.

Table 3 – Acceptability index for the planning of alternatives to the decommissioning of the Marlim and Voador fields.

Decision maker	Risk profile		RAI_i^1	RAI_i^2	RAI_i^3	RAI_i^4	RAI_i^5
Regulator	Bold	A_1	0.05%	0.67%	18.91%	24.80%	55.57%
		A_2	0.27%	2.32%	24.12%	31.78%	41.51%
		A_3	0.07%	1.34%	52.75%	42.92%	2.92%
		A_4	63.91%	35.09%	0.90%	0.10%	0.00%
		A_5	35.70%	60.58%	3.32%	0.40%	0.00%
	Neutral	A_1	0.04%	0.76%	13.07%	28.80%	57.33%
		A_2	0.17%	2.33%	17.56%	38.60%	41.34%
		A_3	0.10%	2.58%	64.22%	31.78%	1.32%
		A_4	70.83%	28.10%	1.05%	0.02%	0.00%
		A_5	28.86%	66.23%	4.10%	0.80%	0.01%
	Conservative	A_1	0.08%	0.70%	10.11%	32.15%	56.96%
		A_2	0.29%	2.00%	12.69%	42.50%	42.52%
		A_3	0.04%	4.24%	71.01%	24.21%	0.50%
		A_4	75.01%	24.14%	0.80%	0.05%	0.00%
		A_5	24.58%	68.92%	5.39%	1.09%	0.02%
Proponent	Bold	A_1	0.00%	0.00%	0.00%	89.51%	10.49%
		A_2	0.00%	0.00%	0.00%	10.49%	89.51%
		A_3	0.00%	0.00%	100.00%	0.00%	0.00%
		A_4	0.00%	100.00%	0.00%	0.00%	0.00%
		A_5	100.00%	0.00%	0.00%	0.00%	0.00%
		A_1	0.00%	0.00%	0.00%	90.44%	9.56%
	Neutral	A_2	0.00%	0.00%	0.00%	9.56%	90.44%
		A_3	0.00%	0.00%	100.00%	0.00%	0.00%
		A_4	0.00%	100.00%	0.00%	0.00%	0.00%
		A_5	100.00%	0.00%	0.00%	0.00%	0.00%
	Conservative	A_1	0.00%	0.00%	0.00%	90.53%	9.47%
		A_2	0.00%	0.00%	0.00%	9.47%	90.53%
		A_3	0.00%	0.02%	99.98%	0.00%	0.00%
		A_4	0.00%	99.98%	0.02%	0.00%	0.00%
		A_5	100.00%	0.00%	0.00%	0.00%	0.00%

Analogous to *CWV*, the amplification factors $CAF_i^c(x)$, equation (15), and the significance factors $CSF_i^c(x)$, equation (16), are then calculated. Concomitantly, through equation (17) the confidence factors CF_i^c of the alternatives are obtained, a probability measure of the alternative A_i occupying the first classification for the vectors $CWV_i^c(x)$, $CAF_i^c(x)$, and $CSF_i^c(x)$.

Finally, the SMAA-ExpTODIM is finalized, obtaining the winning index of the *PWI* pairwise comparison, equation (18).

The different pertinences of the PDF of the parameter ρ, Table 2, represent the way in which the individual DM faces the decision problem, in a conservative, neutral, or bold way, according to the perspectives of the Proponent or Regulator.

Finally, step 9 of the SMAA-ExpTODIM frame of reference is conducted, Fig. 2. The appreciation of the values obtained for the *RAI* of the alternatives, Table 3, as well as the confidence factors, allows for greater acceptability and confidence for alternatives A_4 and A_5, both from the perspective of the Proponent and the Regulator. Fig. 4 presents the $RAI_i^r(x)$ of the alternatives in all ranking positions, revealing the preferential stochastic ranking of the Regulatory DM with conservative profile $A_4 \succ A_5 \succ A_3 \succ A_2 \succ A_1$. In contrast, evaluating the $RAI_i^r(x)$ results of Table 3, from the point of view of the Proponent, only alternative 5 occupies the top of the ranking. For the bold, neutral, or conservative risk profile, in none of the 10^4 iterations, no alternative threatened the preferential stochastic ordering $A_5 \succ A_4 \succ A_3 \succ A_1 \succ A_2$.

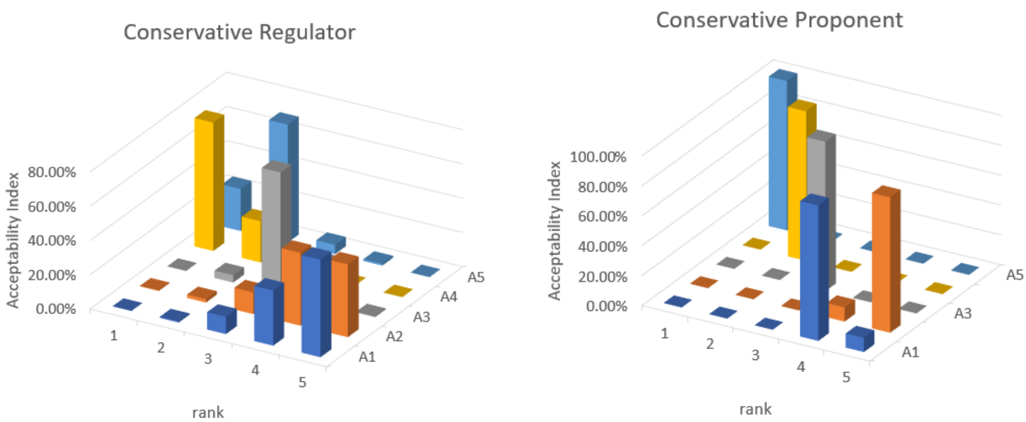

Figure 4 – RAI for Regulator and Proponent of conservative profile.

5 RESULTS AND DISCUSSION

The PDI (Petrobras, 2021) adopts comparative analysis of alternatives, a method of aggregating points in which the chosen alternative is that with the highest score. In the comparative evaluation, there is no difference in weight importance between criteria, and it presents evaluation only from the perspective of the Proponent. Table 4 summarizes the rankings obtained by applying the proposed MCDA SMAA-ExpTODIM, and the comparative assessment of the PDI (Petrobras, 2021).

From Table 4, it is possible to observe greater relevance of alternatives 4 and 5 in the first and second position of the orders obtained in the SMAA-ExpTODIM, with alternative 4 being preferred from the perspective of the Regulator DM, while alternative 5 represents the interest of the Proponent DM. In contrast, alternatives 1 and 2 are the most strongly dominated, as they occupy the last positions in all SMAA-ExpTODIM simulated scenarios.

Table 4 – Ranking of alternatives to the decommissioning of flexible lines in the Marlim and Voador fields.

Decision maker		SMAA-ExpTODIM			PDI
		Bold	Neutral	Conservative	
Regulator	A_1	5	5	5	n/a
	A_2	4	4	4	n/a
	A_3	3	3	3	n/a
	A_4	**1**	**1**	**1**	n/a
	A_5	2	2	2	n/a
Proponent	A_1	4	4	4	5
	A_2	5	5	5	4
	A_3	3	3	3	3
	A_4	2	2	2	2
	A_5	**1**	**1**	**1**	**1**

In addition to risk propensity or risk aversion profiles, the SMAA-ExpTODIM is robust in allowing it to consider, in its stochastic modeling of the problem, the zones of uncertainty in the evaluation of alternatives, as well as the incompleteness of understanding the weights of the criteria.

From the *RAI*, Table 3, it is still possible to verify that from the Regulator's point of view, all the alternatives, in some of the 10^4 iterations, occupied the top of the ranking. In contrast, from the point of view of the Proponent and in all risk profiles, alternative 5 is preferred in all iterations. It is possible to verify, still from Table 3, that the adjustments of the probability distributions to the risk profiles, from bold, neutral, and to the conservative, reinforce the ordering of alternatives. This reveals an increase in robustness and comfort to the DM from the Regulator's perspective, for example, in opting for the ordering $A_4 \succ A_5 \succ A_3 \succ A_2 \succ A_1$.

The SMAA-ExpTODIM proved to be adequate in terms of creating a priori robust decision solutions due to its flexibility and greater scope in representing the areas of uncertainty, ignorance, and complexity of the decision problem.

6 CONCLUSION

The combination of the SMAA technique and the ExpTODIM method, designated in this work as SMAA-ExpTODIM, reveals an expressive range of a priori robustness, allowing the solution of complex problems with consistency. It was capable of covering the antagonistic perspectives of Proponent and Regulatory institutions in ordering the choice of alternatives to the decommissioning of O&G production assets.

Through the SMAA-ExpTODIM approach, the choice of alternative to the decommissioning of the subsea systems of the Marlim and Voador fields takes place in a broad and comprehensive way, considering the areas of uncertainty and adjustments to the position of the Proponent and Regulator DM. The stochastic aspect of SMAA-ExpTODIM allows creating risk appetite profiles, considering different PDF for bold, neutral, and conservative individuals. There is also the differentiation of the Cost and Benefit criteria in the evaluation of alternatives. These characteristics reveal the ability to present a robust choice of alternative to a priori decommissioning, that is, from the beginning of the construction of the decision model. For the composition of the ordering acceptability indices, $\mathrm{RAI}_i{}^r(x)$ revealed the robust stochastic ordering of the SMAA-ExpTODIM.

Incorporating the SMAA stochastic measures in ExpTODIM follows the path identified by Leoneti and Gomes (2021a) of optimizing the parameters of the new φ function, considering that the results provided proved to be very consistent in terms of adherence to the agents' preference, with high levels of robustness of the results with a minimal range of variations.

The application of the SMAA-ExpTODIM revealed a range of robust choices when approaching the decision problem from the antagonistic perspectives of the Proponent and Regulator entities. However, in an effective policy exercise one must consider not only the measurable and contrastable dimensions of the simple parts of the system, which even if complicated, can be technically simulated. Future applications of SMAA-ExpTODIM may consider broader dimensions of the problem, that is, power relations, hidden interests, social participation, cultural restrictions, or other factors capable of becoming relevant variables.

Real-life decision-making situations often preclude assessing how well the underlying assumptions of a decision model are satisfied. In the light of Game Theory, Araújo and Leoneti (2020) deal with new perspectives on how difficult it is for a regulatory agency to equate the different interests of the actors involved in choosing a regulatory regime (concession, sharing, partnerships, or contracting of services) to the O&G exploration and production market. In decommissioning projects, social, operational safety, and environmental factors outweigh technical and economic issues. Therefore, there is room to explore studies in future approaches that analyze the interactions of regulatory bodies in O&G decommissioning projects from the perspective of Game Theory.

In the present study, the stochastic parameters of the SMAA-ExpTODIM application were obtained from the contribution of specialist engineers and consultants working in O&G decommissioning projects. Future research with access to technical experts or DM from regulatory bodies can validate, or even adjust, the probability distributions proposed here.

In decommissioning projects that require public hearings, or where negotiations between the proposing company and the regulatory body are accessible, it is possible to model the interactions between those involved through the proposition of Leoneti and Gomes (2021b). The authors refine the additive multi-attribute utility function (φ) by adjusting the pairwise comparison in iterations of the group decision. Therefore, it is possible to seek the development of a more robust model or adjustments of smaller dispersion in the parameters of the SMAA-ExpTODIM.

Future applications of the SMAA-ExpTODIM approach in decommissioning projects may seek to understand the a priori interaction of other stakeholders (NGOs, community leaders, unions, fishermen's cooperatives, research institutes, etc.) in the decision-making process of an offshore decommissioning project, in order to improve the modeling and importance of criteria to explain the particularities and preferences of each one.

There is also the possibility of conducting documentary research in historical, legislative, and administrative archives of regulatory institutions, or even in files of judicial proceedings. These records can produce a map of the social actors relevant to the offshore decommissioning decision problem.

References

AISSI H & ROY B. 2010. Robustness in Multi-criteria Decision Aiding. In M Ehrgott JR Figueira & S Greco (Eds.), *Trends in Multiple Criteria Decision Analysis*. **142**: 87–121. Springer US. Available at: https://doi.org/10.1007/978-1-4419-5904-1

ANP. 2020. *RESOLUÇÃO Nº 817, DE 24 DE ABRIL DE 2020*. Agência Nacional Do Petróleo, Gás Natural e Biocombustíveis. Available at: https://www.in.gov.br/en/web/dou/-/resolucao-n-817-de-24-de-abril-de-2020-254001378

ANP. 2022. *Painel Dinâmico de Descomissionamento*. Agência Nacional Do Petróleo, Gás Natural e Biocombustíveis. Available at: https://www.gov.br/anp/pt-br/assuntos/exploracao-e-producao-de-oleo-e-gas/seguranca-operacional-e-meio-ambiente/descomissionamento-de-instalacoes

ARAUJO FC & LEONETI AB. 2020. Evaluating the Stability of the Oil and Gas Exploration and Production Regulatory Framework in Brazil. *Group Decision and Negotiation*. **29**(1): 143–156. Available at: https://doi.org/10.1007/s10726-019-09643-4

BELTON V & STEWART TJ. 2002. Multiple Criteria Decision Analysis. In K A Publishers (Ed.), *Multiple Criteria Decision Analysis*. 1st ed. Springer US. Available at: https://doi.org/10.1007/978-1-4615-1495-4

BULL AS & LOVE MS. 2019. Worldwide oil and gas platform decommissioning: A review of practices and reefing options. *Ocean and Coastal Management*. **168**(September 2018): 274–306. Available at: https://doi.org/10.1016/j.ocecoaman.2018.10.024

DURBACH IN & STEWART TJ. 2012. Modeling uncertainty in multi-criteria decision analysis. *European Journal of Operational Research*. **223**(1), 1–14. Available at: https://doi.org/10.1016/j.ejor.2012.04.038

DYSERT LR. 2016. Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Process Industries. In *AACE International Recommended Practices* (Issue 18, p. 16). Available at: http://www.aacei.org/technical/rps/18r-97.pdf

EKE E, IYALLA I, ANDRAWUS J & PRABHU R. 2020. Optimising offshore structures decommissioning - A multicriteria decisionapproach. *Society of Petroleum Engineers - SPE Nigeria*

Annual International Conference and Exhibition 2020, NAIC 2020. **2018**, 1–19. Available at: https://doi.org/10.2118/203760-ms

EKINS P, VANNER R & FIREBRACE J. 2006. Decommissioning of offshore oil and gas facilities: A comparative assessment of different scenarios. *Journal of Environmental Management*. **79**(4), 420–438. Available at: https://doi.org/10.1016/j.jenvman.2005.08.023

FIGUEIRA JR, GRECO S & ROY B. 2009. ELECTRE methods with interaction between criteria: An extension of the concordance index. *European Journal of Operational Research*. **199**(2), 478–495. Available at: https://doi.org/10.1016/j.ejor.2008.11.025

FIGUEIRA J & ROY B. 2002. Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure. *European Journal of Operational Research*. **139**(2), 317–326. Available at: https://doi.org/10.1016/S0377-2217(01)00370-8

FOWLER AM, MACREADIE PI, JONES DOB & BOOTH DJ. 2014. A multi-criteria decision approach to decommissioning of offshore oil and gas infrastructure. *Ocean and Coastal Management*. **87**, 20–29. Available at: https://doi.org/10.1016/j.ocecoaman.2013.10.019

GOMES LFAM & LIMA MMPP. 1991. Todim: Basic and application to multicriteria ranking of projects with environmental impacts. *Foundations of Computing and Decision Sciences*. **16**(4), 113–127.

GOMES LFAM & LIMA MMPP. 1992. From modelling individual preferences to multicriteria ranking of discrete alternatives: A look of prospect theory and additive difference model. *Foudation of Computing and Decision Sciences*. **17**(3), 171–184.

GOMES LFAM & RANGEL LAD. 2009. An application of the TODIM method to the multicriteria rental evaluation of residential properties. *European Journal of Operational Research*. **193**(1), 204–211. Available at: https://doi.org/10.1016/j.ejor.2007.10.046

HENRION M, BERNSTEIN B & SWAMY S. 2015. A multi-attribute decision analysis for decommissioning offshore oil and gas platforms. *Integrated Environmental Assessment and Management*. **11**(4), 594–609. Available at: https://doi.org/10.1002/ieam.1693

KAHNEMAN D & TVERSKY A. 1979. Prospect Theory: An Analysis of Decision Under Risk. *Econometrica*, **47**(2), 263–291.

KAISER MJ. 2019. *Decommissioning Forecasting and Operating Cost Estimation*. Gulf Professional Publishing. Available at: https://doi.org/10.1016/C2018-0-02728-0

KEENEY RL & RAIFFA H. 1993. Decisions with Multiple Objectives. In *IEEE Transactions on Systems, Man and Cybernetics* (1st ed.). Cambridge University Press. Available at: https://doi.org/10.1017/CBO9781139174084

LAHDELMA R, HOKKANEN J & SALMINEN P. 1998. SMAA - Stochastic multiobjective acceptability analysis. *European Journal of Operational Research*. **106**(1), 137–143. Available at: https://doi.org/10.1016/S0377-2217(97)00163-X

LAHDELMA R & SALMINEN P. 2001. SMAA-2: Stochastic multicriteria acceptability analysis for group decision making. *Operations Research*. **49**(3), 444–454. Available at: https://doi.org/10.1287/opre.49.3.444.11220

LAHDELMA R & SALMINEN P. 2010. Stochastic Multicriteria Acceptability Analysis. In M Ehrgott JR Figueira & S Greco (Eds.), *Trends in Multiple Criteria Decision Analysis* (142nd ed., pp. 285–315). Springer.

LEONETI AB & GOMES LFAM. 2021a. A novel version of the TODIM method based on the exponential model of prospect theory: the ExpTODIM method. *European Journal of Operational Research*. **0**(29), 1–14. Available at: https://doi.org/10.1016/j.ejor.2021.03.055

LEONETI AB & GOMES LFAM. 2021b. Modeling multicriteria group decision making as games from enhanced pairwise comparisons. *Operations Research Perspectives*. **8**, 100194. Available at: https://doi.org/10.1016/j.orp.2021.100194

MARTINS I, BAHIENSE L, INFANTE CED & ARRUDA EF. 2020. Dimensionality reduction for multi-criteria problems: An application to the decommissioning of oil and gas installations. *Expert Systems with Applications*. **148**(June 2020). Available at: https://doi.org/10.1016/j.eswa.2020.113236

MARTINS I, MORAES FF, TÁVORA G, SOARES HLF, INFANTE CE, ARRUDA EF, BAHIENSE L, CAPRACE J, & LOURENÇO MI. 2020. A review of the multicriteria decision analysis applied to oil and gas decommissioning problems. *Ocean and Coastal Management*. **184**(October 2019). Available at: https://doi.org/10.1016/j.ocecoaman.2019.105000

NOVEMSKY N & KAHNEMAN D. 2005. The Boundaries of Loss Aversion. *Journal of Marketing Research*, **42**(2), 119–128. Available at: https://doi.org/10.1509/jmkr.42.2.119.62292

OGU K. 2020. *Decommissioning insight 2020*. UK Oil and Gas Industry Association. Available at: https://oilandgasuk.co.uk/product/decommissioning-insight-report/

PETROBRAS. 2021. *PDIs Conceituais dos Sistemas de Marlim e Voador*. Available at: https://www.gov.br/anp/pt-br/assuntos/exploracao-e-producao-de-oleo-e-gas/seguranca-operacional-e-meio-ambiente/arq/ppdi/pdis-conceituais-marlim-voador.pdf

REPSOL. 2017. *UKCS Decommissioning Programme*. Available at: https://www.repsol.no/imagenes/repsolpornr/no/decommissioning_programme_tcm89-119886.pdf

ROY B. 2016. Paradigms and Challenges. In S Grego, M Ehrgott & JR Figueira (Eds.), *Multiple Criteria Decision Analysis* (2nd ed., pp. 19–39). Springer. Available at: https://doi.org/10.1007/978-1-4939-3094-4_2

SCHROEDER DM & LOVE MS. 2004. Ecological and political issues surrounding decommissioning of offshore oil facilities in the Southern California Bight. *Ocean and Coastal Management*. **47**(1–2). Available at: https://doi.org/10.1016/j.ocecoaman.2004.03.002

SHELL. 2017. *Brent Field Decomissioning: Comparative Assessment Procedure*. Available at: https://www.shell.co.uk/sustainability/decommissioning/brent-field-decommissioning/brent-field-decommissioning-programme/_jcr_content/par/tabbedcontent/tab_1385449832/textimage.stream/1486471899349/14e9687bafecccbbd0a211b8f518c14545018f04/brent-decom-comp

SHELL. 2020. *PDI Conceitual Plataforma Fluminense*. Available at: https://www.https//www.gov.br/anp/pt-br/assuntos/exploracao-e-producao-de-oleo-e-gas/seguranca-operacional-e-meio-ambiente/arq/ppdi/pdi-conceitual-plataforma-fluminense.pdfnca-operacional-e-meio-ambiente/arq/shell_brasil_pdi_conceitual_bjsa-publicacao.pdf

STEWART TJ & DURBACH I. 2016. Dealing with Uncertainties in MCDA. In S Grego, M Ehrgott & JR Figueira (Eds.), *Multiple Criteria Decision Analysis State of the Art Surveys* (2nd ed., pp. 467–496). Springer. Available at: https://doi.org/10.1007/978-1-4939-3094-4_12

TERVONEN T & FIGUEIRA JR. 2008. A survey on stochastic multicriteria acceptability analysis methods. *Journal of Multi-Criteria Decision Analysis*. **15**(1–2), 1–14. Available at: https://doi.org/10.1002/mcda.407

TERVONEN T & LAHDELMA R. 2007. Implementing stochastic multicriteria acceptability analysis. *European Journal of Operational Research*. **178**(2), 500–513. Available at: https://doi.org/10.1016/j.ejor.2005.12.037

UN. 1958. United Nations Convention on the Continental Shelf. *Treaty Series*. **499**(6), 311. Available at: https://legal.un.org/ilc/texts/instruments/english/conventions/8_1_1958_continental_shelf.pdf

UN. 1995. United Nations Convention on the Law of the Sea. *Ocean Development and International Law*, **26**(4), 391–412. Available at: https://doi.org/10.1080/00908329509546068

ZHANG W, JU Y & GOMES LFAM. 2017. The SMAA-TODIM approach: Modeling of preferences and a robustness analysis framework. *Computers and Industrial Engineering*. **114**(October), 130–141. Available at: https://doi.org/10.1016/j.cie.2017.10.006

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On article **Decommissioning offshore oil and gas production systems with SMAA-ExpTODIM**, with DOI number 10.1590/0101-7438.2023.043.00267436, published on Pesquisa Operacional 43: e267436:

on page 1:

where it reads:
Yarly Queiroz de Lima[1*], Flavio Autran Monteiro Gomes[2] and Alexandre Bevilacqua Leoneti[3]

should read:
Yarly Queiroz de Lima[1*], Luiz Flavio Autran Monteiro Gomes[2] and Alexandre Bevilacqua Leoneti[3]

on pages 3, 5, 7, 9, 11, 13, 15, 17, 19 and 21:

where it reads:
YARLY QUEIROZ DE LIMA, FLAVIO AUTRAN MONTEIRO GOMES and ALEXANDRE BEVILACQUA LEONETI

should read:
YARLY QUEIROZ DE LIMA, LUIZ FLAVIO AUTRAN MONTEIRO GOMES and ALEXANDRE BEVILACQUA LEONETI

on page 22:

where it reads:
LIMA YQ, GOMES FAM AND LEONETI AB. 2023. Decommissioning offshore oil and gas production systems with SMAA-ExpTODIM. *Pesquisa Operacional*, **43**: e267436. doi: 10.1590/0101-7438.2023.043.00267436.

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