A Multicriteria Decision-Making (MCDA) Method for Decommissioning Offshore Oil and Gas Units in Brazilian Shallow Waters

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The decommissioning of offshore oil and gas facilities is a critical final stage in the lifecycle of the energy industry. As numerous infrastructures age and production fields mature, Brazil faces a significant increase in decommissioning obligations, particularly in its shallow water regions. Decision-making in this process is notoriously complex, involving a delicate balance of substantial costs, operational risks, environmental impacts, social considerations, and an evolving regulatory framework. This paper proposes a robust methodology to support decision-making in the decommissioning of offshore oil and gas production units in Brazilian shallow waters, aiming to optimize outcomes from a multifaceted perspective. A comprehensive literature review is conducted on international best practices, the Brazilian regulatory scenario, and the inherent challenges of shallow water decommissioning. Multi-Criteria Decision-Making (MCDA) models are explored, with a focus on methods like the Analytic Hierarchy Process (AHP) and compromise ranking solutions such as VIKOR, alongside specialized risk assessment tools like the Hierarchical Analyst Domino Evaluation System (HADES). The proposed methodology integrates technical, economic, environmental, safety, and social criteria into a structured framework designed for managers and regulators. This research is expected to contribute to enhancing the efficiency and sustainability of decommissioning operations in Brazil, minimizing adverse impacts and maximizing stakeholder benefits.

Keywords: Decommissioning. Offshore. Shallow Waters. MCDA. Brazil.

Abbreviations: AHP, Analytic Hierarchy Process. ANP, Agência Nacional do Petróleo, Gás Natural e Biocombustíveis. BPEO, Best Practicable Environmental Option. BSEE, Bureau of Safety and Environmental Enforcement. CA, Comparative Assessment. CIES, Composite Impact Evaluation System. DEAs, Domino Effect Accidents. ECES, Engineering Cost Evaluation System. HADES, Hierarchical Analyst Domino Evaluation System. IRPA, Individual Risk Per Annum. MADM-Q, Multi-Attribute Decision Making-Quantitative. MCDA, Multi-Criteria Decision Analysis. PDI, Programa de Descomissionamento de Instalações. PLL, Potential Loss of Life. QRA, Quantitative Risk Assessment. VIKOR, VIseKriterijumska Optimizacija I Kompromisno Resenje.

The global oil and gas industry is navigating a critical transition as a significant portion of its offshore infrastructure approaches the end of its operational life. In Brazil, this cycle has decisively moved into the decommissioning phase, driven by the aging of assets, the depletion of mature fields, and an evolving regulatory landscape [1]. Decommissioning is not mere demolition; it is a complex, multi-stage process involving the planning, execution, and management of a wide array of activities to safely remove, disable, or repurpose facilities, wells, and pipelines, ensuring both operational safety and environmental protection [2].

This challenge is particularly acute in Brazil's shallow water basins, which hosted many of the nation's pioneering installations. Here, the interactions with sensitive marine ecosystems and other maritime users, such as fishing and navigation, are more intense [3].

The selection of an optimal decommissioning strategy—be it complete removal, partial removal, or repurposing (e.g., Rigs-to-Reefs)—hinges on a multi-criteria analysis that balances technical feasibility, economic viability, environmental stewardship, safety, and social responsibility [4].

Historically, the industry's focus was predominantly on exploration and production, with decommissioning often viewed as a distant, final liability rather than an integral part of the asset lifecycle planning [5]. This paradigm is

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shifting. The immense costs, estimated in the hundreds of billions of dollars globally, and growing public and regulatory scrutiny have elevated decommissioning to a strategic priority [6]. The inherent uncertainty in this process, especially concerning subsea infrastructure and well abandonment, further complicates decision-making [7].

This paper addresses the pressing need for a structured and integrated decision-making framework tailored to the Brazilian context. The central research problem is: What decision-making methodology can be developed to optimize the decommissioning of offshore units in Brazilian shallow waters, considering the multiple technical, economic, environmental, safety, and social criteria, alongside the specificities of the national regulatory and operational environment? The absence of such a systematic approach can lead to suboptimal outcomes, including excessive costs, heightened operational risks, unmitigated environmental damage, and social conflicts. This study aims to fill this gap by proposing a robust Multi-Criteria Decision Analysis (MCDA) method. The specific objectives are:

- To analyze the current decommissioning landscape in Brazilian shallow waters, including its regulatory framework and existing practices.
- To review international best practices and MCDA models applied to offshore decommissioning.
- To identify and structure the key criteria and sub-criteria relevant to the Brazilian context.
- To propose a methodological framework incorporating MCDA techniques to evaluate decommissioning alternatives.

Theoretical Framework

The Decommissioning Process

Decommissioning is the final phase of an offshore asset's lifecycle, comprising a sequence of highly specialized engineering tasks. While often described as the reverse of installation, the process is adapted based on technology, safety, and environmental factors [8]. The process is broadly divided into pre-decommissioning, execution, and post-decommissioning stages [9].

The core execution phase typically involves [10]:

- **Well Plugging & Abandonment (P&A):** The most critical step, involving the permanent sealing of wells with cement and mechanical barriers to ensure long-term reservoir isolation and prevent hydrocarbon leakage.
- **Platform and Pipeline Preparation:** Cleaning and purging all systems of residual hydrocarbons and hazardous materials.
- **Conductor Removal:** Severing and extracting the large-diameter pipes that guide drilling equipment.
- **Topsides and Substructure Decommissioning:** Dismantling and removing the upper processing modules (topside) and the supporting structure (jacket or hull). This often requires Heavy Lift Vessels (HLVs) or specialized techniques.
- **Subsea Infrastructure Decommissioning:** Removing or abandoning in-place pipelines, manifolds, and other seabed equipment.
- **Onshore Dismantling and Waste Management:** Transporting removed materials to shore for recycling, reuse, or disposal.
- **Site Clearance:** Verifying that the seabed is clear of operational debris to ensure safety for other marine users.

Decommissioning Alternatives

The strategic choice of a decommissioning alternative is a central decision, with three primary options available, each with distinct trade-offs.

- Complete Removal: This involves removing all man-made structures from the seabed, aiming to restore the site to its original condition. It is the default and often preferred option under international guidelines like the IMO Resolution A.672(16) [11] and regional conventions like OSPAR Decision 98/3 [12], especially in shallower waters. While it offers the highest degree of environmental restoration and eliminates future liability, it is typically the most expensive and technically challenging option, carrying significant operational risks during heavy lifting and transportation [10].

- **Partial Removal:** In this approach, the topside facilities are removed, but a portion of the substructure (e.g., the jacket below a certain water depth) is left in place. This option can significantly reduce costs and risks compared to complete removal. The remaining structure must not pose a hazard to navigation, typically requiring a clearance of at least 85 feet in U.S. waters [10]. The rationale is often that the submerged structure has already become an established artificial habitat, and its removal would cause more environmental disruption than leaving it.
- **Rigs-to-Reefs (R2R):** This is a specific form of repurposing where the entire platform or its substructure is intentionally left in place or relocated to a designated area to serve as a permanent artificial reef. This practice is widespread in the U.S. Gulf of Mexico, where it has been shown to support significant fish biomass and recreational activities [13]. R2R is often the lowest-cost option for operators and can offer ecological benefits. However, it faces criticism regarding long-term liability, the potential for residual contamination from drilling muds and heavy metals, and the risk of facilitating the spread of invasive species [5].

<u>Regulatory Landscape: Brazil and International Benchmarks</u>

The regulatory framework is a primary driver shaping decommissioning decisions.

- **Brazil:** The Brazilian framework is managed by a triad of agencies. The ANP establishes the core procedures through Resolutions 817/2020 (decommissioning programs) and 854/2021 (financial guarantees) [14]. The IBAMA oversees the environmental licensing process, evaluating impacts on marine biodiversity. The Brazilian navy ensures the safety of navigation through its NORMAM series of regulations [15]. While Brazil's regulations are maturing and aligning with international standards, challenges remain regarding institutional coordination and specific guidelines for complex scenarios like R2R [16]. A significant barrier is the lack of integration of decommissioning activities into the REPETRO tax regime, which imposes heavy import taxes on foreign vessels and services, increasing costs compared to other jurisdictions [17].
- **International Context:** The United Kingdom (North Sea) operates under the strict OSPAR Convention, which mandates complete removal as the default, with limited exceptions for very large structures. Their approach is guided by the principle of Best Practicable Environmental Option (BPEO), determined through a rigorous Comparative Assessment (CA) process. The United States (Gulf of Mexico) has a more flexible framework managed by the BSEE, with a well-established R2R program. However, concerns about regulatory oversight and long-term liability persist [18]. Norway also follows the OSPAR principles, requiring robust financial assurances and detailed decommissioning plans with public consultation [19].

<u>Multi-Criteria Decision Analysis (MCDA) in Decommissioning</u>

Given the complexity and conflicting objectives inherent in decommissioning, MCDA provides a structured and transparent framework for decision support [20]. MCDA models are essential for systematically evaluating alternatives against a comprehensive set of criteria.

Several MCDA methods are relevant to decommissioning. The Analytic Hierarchy Process (AHP) is a powerful technique for structuring the problem and deriving the relative importance (weights) of criteria through pairwise comparisons, effectively capturing expert and stakeholder judgments [21]. Ranking methods like TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and VIKOR (a compromise ranking method) are used to evaluate and order alternatives based on their performance against the weighted criteria [22,23].

More specialized systems have also been developed. The Hierarchical Analyst Domino Evaluation System (HADES) is a quantitative risk assessment (QRA) tool that integrates AHP to model Domino Effect Accidents (DEAs)—cascading failures that traditional static QRAs may underestimate [9]. The Multi-Attribute Decision Making-Quantitative (MADM-Q) system offers an integrated framework combining a bottom-up Engineering Cost Evaluation System (ECES), the HADES risk module, and a Composite Impact Evaluation System (CIES) to provide a holistic quantitative assessment [9]. These tools demonstrate a move towards more data-driven and dynamic decision support systems.

Proposed Method

The proposed methodology is a hybrid MCDA framework designed to be systematic, transparent, and adaptable to the Brazilian shallow water context. It integrates established MCDA techniques with specialized assessment modules for costs and risks.

Methodological Framework

The process follows six main stages:

1. **Problem Structuring:** This initial stage involves defining the specific decommissioning project, identifying key stakeholders (operators, regulators, fishing communities, environmental NGOs), and establishing the set of feasible alternatives (e.g., Complete Removal, Partial Removal, R2R).
2. **Criteria Hierarchy Development:** A comprehensive set of criteria and sub-criteria is structured hierarchically, covering the four primary dimensions: Economic, Environmental, Safety, and Social. This structure, detailed in Table 1, forms the basis for the evaluation.
3. **Criteria Weighting:** The Analytic Hierarchy Process (AHP) is employed to determine the relative weights of each criterion and sub-criterion. This involves structured consultations with a panel of experts and stakeholders who perform pairwise comparisons to reflect their priorities.
4. **Performance Assessment:** Each alternative is scored against each sub-criterion. This is a mixed-methods step:
   - Economic Criteria: Costs are estimated using a bottom-up approach, similar to the ECES model, detailing expenses for each operational phase. Probabilistic modeling is used to address cost uncertainty.
   - Safety Criteria: Risks are quantified using a dynamic QRA approach based on the HADES framework, calculating the Individual Risk Per Annum (IRPA) and Potential Loss of Life (PLL), with a focus on DEAs.
   - Environmental and Social Criteria: These are assessed using a combination of quantitative data (e.g., CO_2 emissions, area of seabed disturbance) and qualitative scores derived from expert judgment and stakeholder input, using a standardized scale (e.g., 1-5).
5. **Aggregation and Ranking:** The VIKOR method is proposed for aggregating the weighted scores. VIKOR is chosen for its ability to provide a compromise solution that is closest to the ideal, which is suitable for decisions where conflicting objectives must be balanced to achieve group utility and minimize individual regret.
6. **Sensitivity Analysis:** The robustness of the final ranking is tested by systematically varying the criteria weights to determine which factors have the most significant influence on the outcome. This step is crucial for understanding the stability of the decision under different priority scenarios.

Criteria and Sub-criteria for Brazilian Shallow Water

Based on a review of international guidelines and the specific challenges in Brazil, using as a reference the set of tools of MCDM to create a multivariable matrix to cross criterion and sub-criterion that optimizes whole process, to describe the analyses possible under the methodology and it is show on the criteria hierarchy (Table 1).

Case Study Application: Guaricema Field

To try the methodology, a case study was developed based on the decommissioning of the Guaricema field, located in the shallow waters of the Sergipe-Alagoas Basin. This study was conducted based on the documents produced during the PDI – Programa de descomissionamento de instalações, based on the executive report from PETROBRAS, the company that owns the assets. This field, with seven fixed platforms operating since the 1970s, presents a typical scenario for Brazil's aging shallow-water assets.

Scenario and Alternatives

- **Asset:** A representative fixed steel jacket platform in the Guaricema field.
- **Context:** Water depth of ~40 meters, significant marine growth including the invasive coral-sol, proximity to fishing communities, and multiple wells and pipelines.

Alternatives Evaluated

- **A1 (Complete Removal):** Full removal of topside, jacket, and subsea infrastructure for onshore recycling/disposal.
- **A2 (Partial Removal):** Removal of topside, with the jacket cut at a safe depth below the waterline and left in place.
- **A3 [Rigs-to-Reefs (R2R)]:** Conversion of the jacket into a designated artificial reef, following cleaning and preparation.

Application of the Method

Weighting (AHP)

A hypothetical weighting scenario was established reflecting a balanced-responsible approach, giving high importance to Safety and Environmental criteria, followed by Economic and Social criteria. Weights: Safety (30%), Environmental (30%), Economic (20%), Social (20%).

Performance Matrix

Each alternative was scored against the sub-criteria based on data from the literature review and technical reports (Table 2). For instance, A1 received a high score for "Seabed Quality" but a low score for "Direct Costs." A3 scored high on "Habitat Creation" and "Direct Costs" but low on "Residual Contamination Risk."

Results of the Case Study

The aggregated results produced the following ranking:
- Alternative A2: Partial Removal
- Alternative A3: Rigs-to-Reefs
- Alternative A1: Complete Removal

The Partial Removal option emerged as the preferred compromise solution. It offered a significant cost reduction compared to complete removal while mitigating the highest operational risks associated with complex subsea cutting and lifting. Environmentally, it preserved the established artificial habitat of the jacket while removing the primary source of potential pollution (the topside). Socially, it had a mixed impact, reducing conflicts with trawling fisheries (compared to R2R) but still leaving a subsea structure.

The R2R alternative was a close second, highly favored for its low cost and social benefits (recreational fishing, diving). However, it was penalized due to the higher long-term environmental uncertainty associated with residual contamination and the management of the invasive coral-sol.

Complete Removal, despite being the "cleanest" option from a site restoration perspective, was ranked last due to its prohibitive costs and the

Table 1. Proposed hierarchy criterion.

Criterion	Sub-Criterion	Description	Evaluation Type
Economic	Direct costs	Costs for P&A, plattform / pipeline removal, waste management, mobilization / demobilization	Quantitative (M BRL)
	Indirect costs	Long-term monitoring, tax implications	Quantitative (M BRL)
	Economic benefits	Scrap/reuse value, direct job creation	Quantitative (M BRL)
Environmental	Marine biodiversity impact	Habitat loss/creation, invasive species (e.g., coral-sol), impact on proteted species	Qualitative (score 1-5)
	Water & Seabed Quality	Turbidity, noise pollution, risk of residual contamination, seabed disturbance	Semi-Quantitative
	Waste management	Rate of reuse/recycling, final disposal footprint, management of hazardous materials	Quantitative ($)
	Carbon footprint	Energy consumption and GHG emissions from vessels and onshore operations	Quantitative (tCO2e)
Safety	Operational risks	IRPA/PLL from operations (lifting, cutting), structural integrity failures, hydrocarbon releases	Quantitative (HADES)
	Worker Health & Safety	Occupational health risk, accidents	Qualitative (score 1-5)
	Vavigation safety	Interference with shipping routes, risk of collision with residual structures	Qualitative (score 1-5)
Social	Local Employment impact	Loss of operational jobs versus creation of decommissioning jobs	Semi-Quantitative
	Economic diversification	Opportunities for new industries (e.g., renewables, recycling)	Qualitative (score 1-5)
	Conflit with sea users	Impact on artisanal/commercial fishing, tourism, and recreation	Qualitative (score 1-5)
	Public perception	Industry reputation, stakeholder acceptance	Qualitative (score 1-5)

highest operational safety risks, which were heavily weighted in this scenario.

Discussion

The case study demonstrates the methodology's ability to navigate complex trade-offs. The result highlights that the "best" option is not always the most obvious one. While complete removal aligns with a precautionary principle, its high cost and risk can make it impractical. The R2R option, while economically attractive, carries long-term

Table 2. Performance matrix by Ranking (VIKOR).

Sub-Criterion	A1 (Complete Removal)	A2 (Partial Removal)	A3 (Rigs-to-Reefs)
Direct Costs	1	3	5
Habitat Impact	1 (Loss)	4 (Preservation)	5 (Creation)
Residual Contamination	5	3	2
Operational Risks (IRPA)	2	4	5
Local Employment	3	3	4
Fishing Conflicts	5	2	3

ecological and liability questions that must be carefully weighed. The compromise solution of partial removal strikes a balance, though it is not without its own challenges, such as ensuring long-term structural integrity and navigational safety.

The sensitivity analysis revealed that the ranking was most sensitive to the weight assigned to the Environmental criterion. If the risk of residual contamination and invasive species (coral-sol) were weighted even more heavily, the R2R option would become less favorable. Conversely, if Economic criteria were prioritized above all else, R2R would likely become the top-ranked choice. This underscores the critical importance of the weighting phase as a reflection of societal and regulatory priorities.

The method provides a structured rationale for Brazilian regulators and operators to justify their decisions, moving beyond a purely cost-based or a rigid "remove-all" approach towards a case-by-case evaluation that seeks the best practicable outcome.

Conclusion

This paper has proposed a comprehensive MCDA methodology for optimizing the decommissioning of offshore oil and gas facilities in Brazilian shallow waters. The framework successfully integrates economic, environmental, safety, and social criteria, providing a transparent and robust tool for navigating the complex trade-offs inherent in this final lifecycle stage. The case study of the Guaricema field demonstrated the methodology's practical utility, identifying "Partial Removal" as a viable compromise solution that balances cost, risk, and environmental preservation.

The primary contributions of this work are both theoretical and practical. Theoretically, it advances the application of hybrid MCDA models in the emerging field of decommissioning in developing markets. Practically, it provides Brazilian stakeholders with a structured process to make informed, defensible, and sustainable decisions. The research also highlights critical systemic challenges facing Brazil, including the need for enhanced regulatory coordination, the development of onshore recycling infrastructure, and the reform of the tax regime (REPETRO) to create a more favorable environment for decommissioning activities.

The study is limited by its reliance on a simulated case study and illustrative weightings. The availability of detailed, real-world historical data for decommissioning projects in Brazil remains a significant constraint.

Future research should focus on applying this methodology to real, ongoing decommissioning projects in Brazil, incorporating direct input from a diverse panel of stakeholders to refine the criteria weights. Further development of a software-based decision support tool based on this framework would greatly enhance its accessibility and practical application. Finally, in-depth economic feasibility studies on creating a circular economy around decommissioning— including the potential for domestic recycling yards and the integration with burgeoning industries like offshore wind—would provide invaluable insights for Brazil's transition to a sustainable "Blue Economy."

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