Sustainable Decommissioning in Engineering Education: Empirical Evidence and Circular Economy Imperatives

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Abstract

The accelerated expansion of large-scale technological infrastructures in recent decades—including offshore oil and gas facilities, wind farms, photovoltaic systems, and data centers—has made more visible a challenge that remains insufficiently embedded in engineering education: the sustainable management of asset end-of-life. Recent studies show that the operationalization of circularity in complex systems still faces conceptual fragmentation, governance difficulties, and methodological limitations, particularly regarding the integration of operational closure, value recovery, and life cycle planning [1]. In this context, Life Cycle Thinking (LCT) plays a central role by enabling the assessment of environmental impacts throughout the entire cycle and by preventing the mere transfer of problems from one phase of the production system to another [2].

In the oil and gas sector, decommissioning has already become a strategic global market, marked by high technical, regulatory, and financial complexity [3]. The literature shows that offshore end-of-life decisions require structured decision-support approaches, such as multi-criteria analysis, capable of integrating environmental, economic, social, and technical dimensions [4]. At the same time, other sectors reinforce the urgency of this agenda: in wind energy, growing concern surrounds the future volume of blade waste and the challenges associated with composite recycling [5]; in the solar sector, regulatory frameworks already require formal decommissioning plans, cost estimates, and financial assurance mechanisms for site removal and restoration [6]; and, in data centers, shutdown processes depend on frameworks aligned with stringent compliance requirements, information security, and lifecycle governance of information assets [7]. In all these cases, decommissioning is no longer an isolated sector-specific issue and has become a strategic stage within Product Lifecycle Management and Sustainable Operations.

Despite these sectoral and regulatory advances, the consolidation of decommissioning as a transversal field of research and education remains fragile. In general, engineering curricula prioritize design, implementation, and operational optimization, but rarely incorporate, in a structured way, end-of-life planning, integration with circular supply chains, risk governance, reverse logistics, and multi-criteria sustainability assessment. This gap is particularly relevant in light of the Brazilian National Curriculum Guidelines for Engineering, which require a systemic, ethical, humanistic education committed to sustainable development [8], but do not provide sufficiently detailed references for the curricular operationalization of such competencies.

Against this background, this study argues for the institutionalization of sustainable decommissioning as a transversal research and education line across engineering disciplines. The article seeks to provide an updated theoretical basis, a systemic methodological approach, and empirical evidence supporting the incorporation of the theme into engineering education, in line with the imperatives of the circular economy, LCT, and multi-actor governance.

Methodologically, the study adopts a multi-method approach, combining a systematic literature review with qualitative empirical investigation. The review was conducted in the Scopus database, using searches in the title, abstract, and keywords fields, based on descriptors related to Engineering Education, Circular Economy, Product Lifecycle

Management, Multi-Criteria Decision Analysis, and Decommissioning, articulated through Boolean operators, with a filter for open-access publications. A total of 91 documents published between 2011 and 2026 were identified, revealing a growing trend of academic interest in the subject. The empirical stage mobilized evidence from a postdoctoral research project developed in Brazil between 2018 and 2024, involving the structured engagement of 168 organizations across 23 workshops, technical meetings, and seminars, including operators, regulators, academic institutions, civil society representatives, and supply chain actors. The content generated through these interaction activities was compiled from structured questionnaires with open-ended questions, completed by 309 participants, excluding duplicate participation. The material was examined through qualitative content analysis, with a focus on identifying gaps, required competencies, and governance challenges.

The results indicate a predominance of technical and environmental approaches, with a marked growth in the literature on wind energy, followed by offshore oil and gas. They also reveal gaps related to the absence of dedicated frameworks, the low standardization of dismantling processes, the scarcity of methods for selecting reusable components, and the limited articulation between decommissioning and engineering education. The empirical findings converge around four structural weaknesses: fragmentation of knowledge across technical, environmental, regulatory, and socioeconomic dimensions; predominance of reactive approaches centered on minimum compliance; absence of structured professional training to integrate circular economy principles into operational planning; and increasing coordination costs resulting from the lack of interdisciplinary frameworks. Despite sectoral heterogeneity, the data point to three core transversal competencies: lifecycle systems thinking, integrated sustainability assessment, and multi-actor governance management.

Based on these results, the study proposes an academic framework for sustainable decommissioning structured around five pillars: Design for Decommissioning from the earliest project stages; multi-criteria decision analysis; circular supply chain and reverse logistics modeling; regulatory integration, governance, and stakeholder engagement; and environmental, infrastructural, and informational risk management. By positioning decommissioning as a transversal discipline, the article contributes to consolidating it as a field of lifecycle governance and provides support for updating engineering curricula toward education more aligned with circularity, systemic resilience, and long-term sustainability

Keywords: Sustainable Decommissioning; Engineering Education; Circular Economy; Product Lifecycle Management.

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