Development of a Strategic Decision-Making Framework for Transitioning to a Circular Economy in Mining: A Hybrid SWOT–Fuzzy VIKOR Approach

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Abstract

The transition to a circular economy (CE) in the mining industry constitutes a complex decision-making challenge that confronts managers with conflicting objectives (economic, environmental, and social) and data uncertainty. This study aims to bridge the gap between theory and practice by proposing an innovative hybrid framework (SWOT–Fuzzy VIKOR) for prioritizing CE strategies. The proposed framework integrates qualitative expert analysis through SWOT analysis and the formulation of TOWS strategies with the quantitative evaluation of a fuzzy multi-criteria decision-making model (Fuzzy VIKOR). The research was conducted as a case study in a copper mining complex located in the northwest of the country. The results indicate that strategies based on human capital development (M1), with a score of Q = 0.00, and stakeholder management (M2), with a score of Q = 0.49, are identified as the primary priorities. These findings suggest that, prior to making large-scale technical investments, managers should focus on strengthening human and social infrastructures as essential prerequisites for a successful transition toward sustainability. This framework provides a practical and robust tool for strategic decision-making in heavy industries.

Keywords: *Circular economy, SWOT analysis, Fuzzy VIKOR model, strategic decision-making, sustainable management, Sungun copper mine.*

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1. Introduction

The concept of the circular economy (CE) has emerged as a transformative paradigm in response to the growing environmental degradation, resource depletion, and inefficiencies associated with traditional linear economic models of “take–make–dispose.” Unlike linear systems, the circular economy emphasizes resource efficiency, waste minimization, reuse, recycling, and the regeneration of natural systems, thereby fostering a balanced integration of economic growth and environmental sustainability [1]. This paradigm shift is particularly critical in resource-intensive industries such as mining, where extraction activities inherently generate large volumes of waste, environmental risks, and socio-economic externalities. Consequently, transitioning toward CE principles in mining is not merely an environmental imperative but also a strategic necessity for long-term competitiveness and sustainability.

In recent years, the integration of circular economy principles with industrial practices has gained significant traction, particularly with the advancement of digital technologies and Industry 4.0. Emerging technologies such as big data analytics, artificial intelligence, and smart supply chain systems have been identified as key enablers for enhancing circularity, improving resource utilization, and strengthening supply chain resilience [2, 3]. These technologies facilitate real-time monitoring, predictive maintenance, and data-driven decision-making, which are essential for optimizing circular processes and reducing inefficiencies. Moreover, the integration of CE with digital supply chains has been shown to enhance operational transparency and resilience, thereby enabling organizations to respond more effectively to environmental and market uncertainties [4].

Despite the growing recognition of CE benefits, the implementation of circular practices remains a complex and multifaceted challenge, particularly in developing countries and traditional industries. Organizational barriers such as lack of expertise, resistance to change, and inadequate infrastructure often hinder the adoption of CE strategies [5]. Additionally, external challenges including regulatory uncertainty, market volatility, and stakeholder pressures further complicate the transition process. These complexities necessitate the development of structured and systematic decision-making frameworks that can effectively integrate qualitative insights with quantitative evaluation methods.

Strategic decision-making in the context of CE transition involves multiple, often conflicting criteria, including economic viability, environmental impact, social acceptability, and technological feasibility. Multi-criteria decision-making (MCDM) methods have been widely applied to address such complexities by providing a systematic approach for evaluating and prioritizing alternatives [6]. These methods enable decision-makers to incorporate diverse criteria and stakeholder perspectives, thereby enhancing the robustness and transparency of strategic decisions. Among the various MCDM techniques, the VIKOR method has gained prominence due to its ability to identify compromise solutions that balance group utility and individual regret [7].

The integration of fuzzy logic into MCDM methods further enhances their applicability in real-world decision-making scenarios characterized by uncertainty and imprecision. Fuzzy VIKOR, in particular, allows for the incorporation of linguistic assessments and subjective judgments, thereby improving the reliability of evaluation outcomes [8]. This capability is especially relevant in the context of CE transition, where data may be incomplete or uncertain, and expert opinions play a critical role in decision-making. Furthermore, hybrid approaches that combine qualitative strategic tools with quantitative MCDM techniques have been increasingly advocated to address the limitations of single-method frameworks [9].

One of the most widely used qualitative tools for strategic analysis is the SWOT (Strengths, Weaknesses, Opportunities, Threats) framework, which provides a structured approach for identifying internal and external factors influencing organizational performance. The extension of SWOT into the TOWS matrix enables the formulation of strategic alternatives by systematically linking internal capabilities with external conditions [10]. This approach facilitates the development of actionable strategies that are aligned with organizational strengths and market opportunities while mitigating weaknesses and threats. In the context of CE transition, SWOT/TOWS analysis can provide valuable insights into the specific challenges and opportunities faced by organizations, thereby informing strategic planning processes.

The need for integrated decision-making frameworks that combine SWOT/TOWS analysis with MCDM methods has been highlighted in recent literature. Such hybrid approaches enable the translation of qualitative strategic insights into quantifiable evaluation metrics, thereby bridging the gap between strategic formulation and operational decision-making [9]. By incorporating both qualitative and quantitative dimensions, these frameworks provide a comprehensive basis for prioritizing strategies and allocating resources effectively.

In addition to methodological considerations, the role of human and organizational factors in CE transition has received increasing attention. Human resource management practices, organizational culture, and stakeholder engagement are critical determinants of successful implementation. Studies have shown that the alignment of HR practices with sustainability goals can significantly enhance the adoption of circular economy initiatives [11]. Similarly, the integration of artificial intelligence with HRM has been proposed as a means of facilitating organizational transformation and fostering innovation in CE practices [12]. These findings underscore the importance of considering socio-organizational dimensions alongside technical and economic factors in strategic decision-making.

Moreover, the concept of sustainable supply chain management has been closely linked to the circular economy, emphasizing the need for coordinated efforts across the entire value chain. The adoption of CE principles in supply chains can lead to improved resource efficiency, reduced environmental impact, and enhanced economic performance [13]. The integration of digital transformation and circular strategies has been identified as a key driver for achieving sustainable and resilient supply chains, particularly in the face of global disruptions and uncertainties [14].

Another important dimension of CE transition is the role of knowledge management and social capital in facilitating organizational learning and innovation. Effective knowledge sharing and collaboration among stakeholders can enhance the capacity of organizations to adapt to changing environmental conditions and implement sustainable practices [15]. In the mining industry, where operations are complex and resource-intensive, the development of organizational capabilities and knowledge networks is essential for driving innovation and improving performance.

Recent studies have also highlighted the importance of sector-specific approaches to CE implementation. For instance, the application of circular economy principles in healthcare supply chains has demonstrated the need for prioritizing performance indicators that capture both economic and environmental dimensions [16]. Similarly, the integration of CE with lean management practices has been explored in specialized sectors such as dentistry, emphasizing the adaptability of CE concepts across different industries [17]. These studies suggest that while the core principles of CE are universal, their implementation requires context-specific strategies and decision-making frameworks.

In the context of mining, the transition to a circular economy presents unique challenges and opportunities. The industry is characterized by high capital intensity, long project lifecycles, and significant environmental impacts. At the same time, mining operations generate substantial quantities of waste materials, which can be reprocessed and reused to create value. The adoption of CE strategies in mining can therefore contribute to resource efficiency, environmental protection, and economic diversification. However, the complexity of mining systems and the involvement of multiple stakeholders necessitate the use of advanced decision-making tools to identify and prioritize optimal strategies.

Furthermore, the development of sustainable and circular business models requires a holistic approach that integrates technological, organizational, and institutional dimensions. The utilization of bioproducts and innovative technologies has been proposed as a means of enhancing resource efficiency and supporting the transition to a circular economy [18]. Additionally, the integration of Industry 4.0 technologies with CE practices has been shown to enhance environmental resilience and support sustainable development goals [19]. These advancements highlight the evolving nature of CE and the need for continuous innovation in strategic decision-making.

Despite the extensive body of literature on circular economy and decision-making methods, there remains a gap in the development of practical and integrated frameworks tailored to the specific needs of the mining industry. Existing studies often focus on either qualitative strategic analysis or quantitative evaluation methods, without adequately addressing the need for their integration. This gap limits the applicability of theoretical models in real-world decision-making contexts and underscores the need for hybrid approaches that can effectively bridge theory and practice.

Accordingly, the aim of this study is to develop an integrated SWOT–Fuzzy VIKOR framework for prioritizing circular economy strategies in the mining industry, thereby providing a systematic and practical tool for strategic decision-making under conditions of uncertainty.

2. Methodology

This study is applied in terms of objective and descriptive–analytical in terms of methodology, based on a hybrid framework. The research process was designed in two main phases: a qualitative phase (strategy formulation) and a quantitative phase (strategy prioritization).

Through semi-structured interviews with 10 senior managers and key experts from a copper mining complex located in the northwest of the country, the key internal factors (strengths and weaknesses) and external factors (opportunities and threats) associated with the transition to a circular economy were identified.

Strategy Formulation: The identified factors were categorized within the TOWS matrix, leading to the development of four specific and operational strategies that function as decision alternatives within the multi-criteria decision-making (MCDM) model:

T1: Technological Advancement Strategy (SO): Investing in advanced reprocessing technologies to maximize value extraction from tailings and capitalize on metal market opportunities.

M1: Human Capital Development and Organizational Transformation Strategy (WO): Investing in training and workforce empowerment to overcome technical and managerial weaknesses and to leverage governmental opportunities for green development.

T3: Business Resilience Strategy (ST): Focusing on industrial symbiosis to reduce dependence on the primary product and mitigate the threat of price volatility.

M2: Stakeholder Management and Social License Strategy (WT): Strengthening relationships with local communities and regulatory bodies to reduce social and legal risks and to avoid threats arising from local opposition.

Seven key criteria were defined for evaluating the strategies. These criteria encompass multiple dimensions of managerial decision-making.

Table 1. Evaluation Criteria for Strategies

Criterion Code	Evaluation Criterion	Type
C_1	Implementation Cost (Initial Investment)	Negative
C_2	Profitability	Positive
C_3	Technical Risk	Negative
C_4	Environmental Impact	Positive
C_5	Social Impact	Positive
C_6	Strategic Alignment	Positive
C_7	Implementation Speed	Negative

In this study, a fuzzy questionnaire was designed and distributed among 10 experts. The experts evaluated each of the four strategies (T1–M2) against each of the seven criteria (C_1–C_7) using a fuzzy linguistic scale (very low, low, medium, high, very high).

For data analysis, the linguistic evaluations were converted into triangular fuzzy numbers, and the Fuzzy VIKOR algorithm was applied to compute the indices S_i, R_i, and the final score Q_i for each strategy, in order to determine the final ranking.

3. Findings and Results

The analysis of the interviews led to the identification of the following key factors:

Strengths (S): Rich mineral reserves and the presence of a skilled operational workforce.

Weaknesses (W): Lack of expertise in circular economy practices, a traditional organizational structure, and high dependency on water resources.

Opportunities (O): Government incentives for green industries and increasing global demand for copper.

Threats (T): Pressure from local communities, risks of environmental accidents, and high volatility in global copper prices.

These factors were integrated within the TOWS matrix, resulting in the formulation of four strategies (T1 to M2), as described in previous section.

The final results of the Fuzzy VIKOR model calculations are presented in Table 1. A lower Q_i value indicates a better ranking.

Table 2. Final Ranking Results of Strategies Based on the Fuzzy VIKOR Model

Rank	Strategy	Final Score (Q_i)	Group Utility Index (S_i)	Individual Regret Index (R_i)
1	M1 (Human Capital Development)	0.00	138.6	65.4
2	M2 (Stakeholder Management)	0.49	199.3	72.5
3	T3 (Business Resilience / Industrial Symbiosis)	0.60	258.9	55.0
4	T1 (Technological Advancement / Reprocessing)	0.97	412.0	78.8

To ensure the robustness of the results, a sensitivity analysis was conducted on the parameter v. The findings indicate a high level of stability in the ranking outcomes, particularly for the two top-ranked alternatives (M1 and M2).

4. Discussion and Conclusion

The findings of this study provide a structured and empirically grounded prioritization of circular economy (CE) strategies within the mining industry, highlighting the relative importance of human-centric and governance-oriented approaches over purely technological interventions. The Fuzzy VIKOR results clearly indicate that the Human Capital Development and Organizational Transformation strategy (M1) achieved the highest priority (Q = 0.00), followed by the Stakeholder Management and Social License strategy (M2) with Q = 0.49, while the Business Resilience strategy (T3) and Technological Advancement strategy (T1) ranked lower. This ranking reflects a critical insight: the successful transition to CE in complex industrial contexts such as mining is fundamentally contingent upon socio-organizational readiness rather than immediate technological deployment.

The dominance of the M1 strategy underscores the central role of human capital in enabling circular transformation. This finding aligns with recent literature emphasizing that organizational capabilities, employee competencies, and adaptive learning systems are essential drivers of sustainable transitions [11]. In particular, the integration of human resource management practices with sustainability objectives has been shown to significantly enhance organizational readiness for adopting circular practices. Moreover, the conceptual framework proposed by [12] suggests that aligning human resource development with technological and environmental strategies can facilitate systemic transformation. The present findings reinforce this perspective by demonstrating that investments in training, skill development, and organizational change are perceived by experts as the most critical prerequisites for CE implementation in mining environments.

The prioritization of the M2 strategy further highlights the importance of stakeholder engagement and social legitimacy in the transition process. Mining operations are inherently embedded within complex socio-environmental systems, where community acceptance and regulatory compliance play decisive roles. The emphasis on stakeholder management is consistent with the broader literature on sustainable supply chains, which identifies collaboration and transparency as key enablers of circularity [13]. Additionally, the integration of social performance with operational strategies has been recognized as a critical factor for achieving long-term sustainability outcomes [11]. The relatively high ranking of M2 suggests that mitigating social risks and fostering trust with local communities are not merely complementary actions but core strategic priorities.

In contrast, the lower ranking of the Technological Advancement strategy (T1) challenges the common assumption that technological innovation is the primary driver of circular transformation. While advanced reprocessing technologies and Industry 4.0 solutions are undoubtedly important, their effectiveness depends on the existence of supportive organizational and institutional conditions. This finding is consistent with studies indicating that technological solutions alone cannot ensure successful CE implementation without corresponding changes in organizational culture and governance structures [5]. Furthermore, the integration of digital technologies with circular practices requires significant investments in human capital and infrastructure, which may not be immediately feasible in all contexts [4].

The intermediate position of the Business Resilience strategy (T3) reflects its dual role in addressing both economic and environmental uncertainties. The focus on industrial symbiosis and diversification aligns with the principles of CE, which emphasize resource sharing and system-level optimization. Previous research has highlighted the potential of industrial symbiosis to enhance resource efficiency and reduce environmental impacts [1]. However, the relatively lower ranking of T3 suggests that while such strategies are valuable, they may not be perceived as immediate priorities compared to foundational organizational and stakeholder-related interventions.

From a methodological perspective, the integration of SWOT/TOWS analysis with the Fuzzy VIKOR model proved to be effective in capturing both qualitative and quantitative dimensions of strategic decision-making. The SWOT/TOWS framework facilitated the identification of context-specific factors and the formulation of actionable strategies, while the Fuzzy VIKOR method enabled the systematic evaluation and prioritization of these strategies under conditions of uncertainty. This hybrid approach addresses the limitations of single-method frameworks and aligns with previous studies advocating for integrated decision-making models in complex environments [9]. The use of fuzzy logic further enhanced the robustness of the analysis by accommodating the inherent ambiguity in expert judgments, consistent with the findings of [8].

The application of MCDM techniques in this study also contributes to the growing body of literature on decision-support systems for sustainability. As noted by [6], MCDM methods are particularly well-suited for addressing multi-dimensional decision problems involving conflicting criteria. The ability of the VIKOR method to identify compromise solutions is especially relevant in the context of CE, where trade-offs between economic, environmental, and social objectives are inevitable [7]. The results of this study demonstrate the practical applicability of these methods in real-world industrial settings, thereby bridging the gap between theoretical models and managerial practice.

The findings also highlight the significance of aligning CE strategies with broader technological and digital transformation trends. The integration of Industry 4.0 technologies with CE practices has been shown to enhance operational efficiency and environmental performance [3]. However, the relatively lower priority assigned to technology-driven strategies in this study suggests that such integration should be approached incrementally, with a strong emphasis on building organizational capabilities and stakeholder engagement mechanisms. This perspective is supported by research indicating that digital transformation alone is insufficient without complementary organizational changes [2].

Another important implication of the findings is the role of knowledge management and organizational learning in facilitating CE transition. The identification of human capital development as the top priority underscores the need for effective knowledge-sharing mechanisms and collaborative networks. As highlighted by [15], social capital and knowledge management practices are critical for enhancing organizational adaptability and innovation. In the context of mining, where operations are complex and knowledge-intensive, the development of such capabilities is essential for achieving sustainable outcomes.

The sensitivity analysis conducted in this study further strengthens the validity of the results by demonstrating the stability of the ranking outcomes across different parameter values. The consistent prioritization of M1 and M2 indicates that these strategies are robust under varying decision-making conditions, thereby enhancing the reliability of the proposed framework. This robustness is particularly important in uncertain environments, where decision-makers must rely on stable and credible evaluation tools.

Overall, the results of this study provide valuable insights into the strategic priorities for transitioning to a circular economy in the mining industry. The emphasis on human and social dimensions challenges traditional technology-centric approaches and highlights the need for a more holistic perspective that integrates organizational, technological, and institutional factors. By providing a structured and practical decision-making framework, this study contributes to both the academic literature and managerial practice in the field of sustainable development.

The limitations of this study should be acknowledged. First, the research is based on a single case study within a specific mining complex, which may limit the generalizability of the findings to other contexts or industries. Second, the reliance on expert judgments introduces a degree of subjectivity, despite the use of fuzzy logic to mitigate uncertainty. Third, the study focuses on a limited domain, which may not capture all relevant factors influencing CE transition. Finally, the dynamic and evolving nature of circular economy practices implies that the proposed framework may require adaptation over time.

Future research can build upon the findings of this study by expanding the scope of analysis to include multiple case studies across different regions and industries, thereby enhancing the generalizability of the results. Researchers can also explore the integration of additional decision-making methods, such as machine learning or system dynamics, to further improve the accuracy and applicability of strategic evaluations. Moreover, longitudinal studies can provide deeper insights into the implementation and outcomes of CE strategies over time. Finally, future studies can examine the interactions between technological, organizational, and institutional factors in greater detail to develop more comprehensive models of circular transformation.

From a practical perspective, the findings of this study offer several implications for managers and policymakers. Organizations should prioritize investments in human capital development and organizational transformation as foundational steps toward CE adoption. Building strong relationships with stakeholders and enhancing social legitimacy should also be considered critical components of strategic planning. Furthermore, technological investments should be aligned with organizational capabilities and implemented in a phased manner. Policymakers can support this transition by providing incentives, regulatory frameworks, and capacity-building programs that facilitate the adoption of circular practices.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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