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# STRATEGIC IMPLEMENTATION OF THE WASTE MANAGEMENT HIERARCHY IN MINING OPERATIONS: A CASE STUDY OF THE VELIKI KRIVELJ FLOTATION TAILINGS FACILITY

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## Abstract

*Sustainable waste management in the mining sector is critical for minimizing environmental impact and promoting a circular economy. This paper examines the application of the waste management hierarchy as established by the European Union's Waste Framework Directive (2008/98/EC) and its integration into Serbian national legislation. Focusing on a case study of flotation tailings from the Veliki Krivelj tailings pond, the study analyzes specific measures across the five-step hierarchy. The findings demonstrate that while complete prevention of tailings is not possible due to ore characteristics, significant progress can be achieved through progressive reuse in construction and the investigation of recycling potentials.*

***Keywords**: Waste Management Hierarchy, Mining Waste, Flotation Tailings, Sustainability*

## 1. INTRODUCTION

The global mining industry is one of the largest producers of solid waste, with flotation tailings representing a significant portion of this volume. Traditionally, these waste streams were managed through large-scale disposal in tailings storage facilities (TSFs), often posing long-term environmental risks such as acid mine drainage and physical instability. However, the modern regulatory landscape, driven by the principles of the circular economy, demands a shift toward more sophisticated management strategies [1]. The Waste Framework Directive (Directive 2008/98/EC) serves as the cornerstone of European waste policy, introducing the waste management hierarchy as a legally binding framework. This hierarchy prioritizes waste prevention and resource recovery over traditional disposal methods. In the Republic of Serbia, this directive has been transposed into the national Law on Waste Management, mandating that industrial operators, including mining companies, adopt the best available practices to minimize their environmental footprint [2]. This paper provides a detailed analysis of how these hierarchical principles are applied to the management of flotation tailings at the Veliki Krivelj facility. By evaluating the specific measures proposed for each level of the hierarchy, the study aims to highlight the challenges and opportunities inherent in transitioning toward sustainable mining waste management.

## 2. LEGAL AND CONCEPTUAL FRAMEWORK

### 2.1. The Waste Framework Directive (2008/98/EC)

The EU Waste Framework Directive (WFD) establishes the fundamental definitions and concepts related to waste management. It defines waste not merely as a burden but as a potential resource. Article 4 of the WFD makes the waste hierarchy legally binding, requiring Member States to implement legislation that encourages the options that deliver the best overall environmental outcome [3].

### 2.2. The Serbian Regulatory Context

In accordance with the new Law on Waste Management ("Official Gazette of the Republic of Serbia", No. 109/2025), Article 6 defines the hierarchy principle. This alignment with EU standards is part of Serbia's broader effort to modernize its industrial sectors and improve environmental protection [2].

### 2.3. The Waste Management Hierarchy

The hierarchy is often visualized as an inverted pyramid, consisting of five distinct levels:

1) *Prevention*: The most preferred option, focusing on reducing the quantity and toxicity of waste at the source.
2) *Reuse*: Utilizing waste materials for the same or different purposes without significant processing.
3) *Recycling*: Processing waste into new products or raw materials.
4) *Recovery*: Extracting energy or other value from waste that cannot be recycled.
5) *Disposal*: The least preferred option, involving land-filling or incineration without energy recovery

## 3. METHODOLOGY

The evaluation of waste management strategies at the Veliki Krivelj facility, as part of the Waste Management Plan, followed a multi-disciplinary approach, integrating technical, environmental, and regulatory perspectives. The methodology was structured into four distinct phases to ensure a comprehensive assessment of the waste management hierarchy's implementation.

### 3.1. Process Auditing and Baseline Establishment

Initially, a comprehensive audit of the flotation process was conducted to establish a baseline for waste generation. This also involved sampling and chemical and physical characterization of flotation tailings. The primary goal was to quantify the "unavoidable" waste stream and identify potential points for process optimization.

### 3.2. Characterization of Flotation Tailings

A detailed chemical and physical characterization of the tailings was performed. This included:

1) chemical characterization of mining waste – determination of potentially hazardous substances
2) physicochemical characterization of the leaching behavior of mining waste
3) physicochemical characterization of the toxicity of mining waste in accordance with the toxicity characteristic leaching procedure (TCLP)
4) static testing of mining waste

### 3.3. Regulatory and Best Practice Review

The plan involved a thorough review of the current operational practices against the EU Waste Framework Directive's best available techniques (BAT) and the Serbian Law on Waste Management. This phase focused on identifying gaps between current practices and the ideal implementation of the waste hierarchy.

### 3.4. Development of a Mining Waste Management Plan

Finally, a Mining Waste Management Plan was developed, defining, among other aspects, the basic principles and measures for the responsible management of flotation tailings. The Plan proposes measures and management procedures for flotation tailings in accordance with the waste management hierarchy. Among other measures, further investigations are proposed based on an analogy with similar mineral raw materials, with the aim of reducing the quantity of waste generated and promoting more rational use of resources. The Plan provides a basis for the systematic improvement of flotation tailings management and the application of circular economy principles in the mining sector.

## 4. CASE STUDY: VELIKI KRIVELJ FLOTATION TAILINGS

The Veliki Krivelj mine, operated by Zijin Copper, is a major copper mining operation in eastern Serbia. The flotation concentration process generates vast quantities of tailings, which are stored in dedicated facilities. Field 0 of the Veliki Krivelj TSF is the focus of the current waste management plan [4].

### 4.1. Tailings Characteristics and Environmental Risk

Flotation tailings are finely ground rock particles left over after the valuable minerals have been extracted. Due to the low concentration of valuable minerals in the raw ore, the volume of tailings produced is substantial. The tailings primarily consist of silicate and aluminosilicate minerals, but may also contain residual sulfides. If not managed correctly, these sulfides can oxidize, leading to acid mine drainage (AMD), which poses a significant threat to local water resources. This necessitates a robust management plan that goes beyond simple disposal and actively seeks to mitigate environmental risks through hierarchical management.

### 4.2. Operational Monitoring and Reporting

A critical component of the management plan is the rigorous monitoring and reporting system. The plan specifies daily verbal reporting, monthly production balance and performance analysis, and a comprehensive annual report. This ensures that the Flotation Plant Manager, Chief Engineer, and Tailings Storage Facility Manager have real-time data to optimize the process and ensure compliance with the waste hierarchy.

## 5. ANALYSIS OF THE WASTE MANAGEMENT PLAN

The waste management plan for Field 0 at Veliki Krivelj implements the hierarchical approach through specific technical and administrative measures. These measures are summarized in Table 1.

At the top of the hierarchy, prevention is prioritized. In the context of flotation, this involves maximizing the recovery rate of valuable minerals. While the generation of tailings is an inherent part of the process, continuous optimization of the flotation reagents and technical parameters can slightly reduce the mass of waste produced per unit of product.

**Table 1.** *Waste Management Plan for Flotation Tailings at Field 0 of Veliki Krivelj TSF*

| Level | Measure | Justification |
|---|---|---|
| Prevention | Process optimization to minimize waste quantity. | Generation is unavoidable due to low mineral content; optimization is the primary reduction tool. |
| Reuse | Construction of dams and embankments using cyclone sand. | Progressive construction of TSF structures throughout the mine life. |
| Reuse | Use as an additive in cement, brick, and glass industries. | Material properties may be suitable for various industrial applications based on analogy with similar raw materials. |
| Reuse | Preparation of paste backfill for underground voids. | Filling mine voids improves stability and reduces surface disposal needs. |
| Recycling | Recovery of valuable components via hydrometallurgy. | Potential for extracting secondary minerals from tailings, based on analogy with similar raw materials |
| Recovery | Not applicable. | Mining tailings typically lack energy recovery potential. |
| Disposal | Controlled deposition in the flotation TSF. | Final disposal for quantities that cannot be reused or recycled. |

Reuse represents the most significant opportunity for diversion from disposal at Veliki Krivelj. The plan identifies three main pathways:

1) **Structural Use**: Using cyclone sand for dam construction is a standard industry practice that significantly reduces the need for external construction materials.
2) **Industrial Additives**: The tailings can serve as raw materials for the construction industry, potentially replacing primary raw sand or clay in brick and cement manufacturing [5].

3) **Backfilling**: Paste backfill technology allows for the safe disposal of tailings underground, providing structural support to the mine and reducing the surface footprint of the TSF.

Recycling in this context refers to the secondary extraction of minerals. With advances in hydrometallurgy, tailings that were once considered waste can be re-processed to recover trace elements or residual copper. Energy recovery, however, is generally not applicable to mineral tailings as they lack organic content.

## 6. DISCUSSION

The implementation of the waste hierarchy at Veliki Krivelj illustrates the transition from a linear "extract-use-dispose" model to a more circular approach. By viewing tailings as a potential raw material for other industries, the mining operation can decouple its growth from environmental degradation. The use of tailings in construction not only reduces the volume of waste disposed of in TSFs but also reduces the demand for primary raw materials, thereby lowering the overall carbon footprint of the construction sector.

However, several challenges remain. The economic feasibility of transporting tailings for use in the cement or brick industries depends on the proximity of these facilities to the mine. High transportation costs can often render these reuse options uncompetitive compared to local primary raw materials. Furthermore, the technical requirements for paste backfill require significant capital investment in pumping and mixing infrastructure. The transition to a hierarchical approach therefore requires not only technical innovation but also supportive policy frameworks and economic incentives.

Despite these challenges, the hierarchical approach provides a clear roadmap for improvement. By shifting the focus from "how to dispose" to "how to use," the mine can reduce its long-term liability and environmental impact. The integration of daily, monthly, and annual reporting ensures that waste management remains a central part of operational management. This systematic approach is essential for achieving long-term sustainability and maintaining the social license to operate in an increasingly environmentally conscious global market [6].

As mining operations continue to expand to meet the growing global demand for critical minerals, the importance of sustainable waste management will only increase. Future developments at Veliki Krivelj could include the exploration of bio-hydrometallurgical processes for the recovery of trace elements from tailings, potentially unlocking new value streams while further reducing the environmental toxicity of the final waste product. Collaborative efforts among the mining industry, academia, and the construction sector will be crucial for developing innovative solutions that align with the principles of the circular economy and contribute to the long-term sustainability and viability of the mining sector.

## 7. CONCLUSION

The waste management hierarchy is a powerful tool for guiding industrial operations toward sustainability. As demonstrated by the Veliki Krivelj case study,

applying these principles to mining waste requires a combination of process optimization, innovative reuse, and rigorous monitoring. While disposal remains a necessary part of the process, the systematic prioritization of prevention and reuse significantly enhances the environmental performance of the mining operation. Future research should focus on the long-term stability of reused tailings in construction and the development of cost-effective secondary recovery technologies.

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