SUSTAINABLE REHABILITATION OF OPENCAST MINES

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ABSTRACT
The world's population growth and mineral resource mining are accelerating due to planned energy transitions and rising demand for critical minerals, intensifying environmental, social, and economic challenges. Sustainable management of opencast mines now prioritizes progressive rehabilitation to minimize costs. This ongoing process requires a meticulously planned approach, supported by research and continuous monitoring, to assess and mitigate risks throughout the mine's lifecycle. Successful rehabilitation, exemplified by projects like the Drmno opencast coal mine's dump rehabilitation, hinges on integrating sustainability into all phases, employing defined criteria, technological processes, developmental dynamics, investments, and rigorous monitoring.

Introduction

Rehabilitation of opencast mines and dumps includes planning, designing, and constructing landforms with the establishment of sustainable ecosystems or alternative vegetation, depending on the intended post-mining land use.

Planned mine rehabilitation should achieve three primary objectives:

1. Long-term stability and sustainability of landforms, soil, and site hydrology.
2. Partial or full restoration of ecosystems to provide habitat for biota and benefits for people.
3. Prevention of environmental degradation of the closed mine and its surrounding area.

Rehabilitation is a key component of opencast mine closure planning, and effective and early planning helps minimize rehabilitation costs. Progressive rehabilitation can provide an early indication of whether the mine closure and site abandonment goals are realistic and achievable. Successful sustainable rehabilitation is a continuous process involving constant improvement of outcomes, based on specific knowledge of the site, research, and monitoring of timely implementation [5, 6, 7].

In this context, opportunities and threats should be identified early so that mining operations do not undermine the effectiveness of planned rehabilitation. Any delays result in postponed investments, which also delay the implementation of closure after the mine's operational lifespan, increasing costs and, in some cases, unnecessarily extending the commitments undertaken to sustainably achieve rehabilitation goals [1, 3, 8]. The principles of sustainable progressive rehabilitation are shown in Figure 1.

Figure 1 Principles of sustainable and progressive rehabilitation of the mining area during the operation of an opencast mine

Failure to meet regulatory obligations also leads to increased oversight and additional restrictions for companies, higher compliance costs, and potential legal expenses. In the worst-case scenario, this can result in reputational damage, loss of the company's social license to operate, project delays, and limited future access to resources.
Conversely, demonstrated sustainable outcomes and high-quality rehabilitation results position a company as a development partner for government regulators and local communities.
The importance of rehabilitation with reclamation as part of the mine closure process is also reflected in a growing number of professional and scientific publications, as well as widely accepted international standard systems such as ISO 31000, ISO 14000, and ISO 21795 [2, 5, 6].

1 Planning the Rehabilitation of Opencast Mines

Rehabilitation with reclamation of opencast mines is a costly process, and financial resources for repeating unsuccessful rehabilitation efforts are often limited. Therefore, it is important to consistently follow an adopted plan in order to achieve acceptable and sustainable outcomes.
For successful implementation, rehabilitation planning should ideally include five common development phases, as shown in Figure 2.

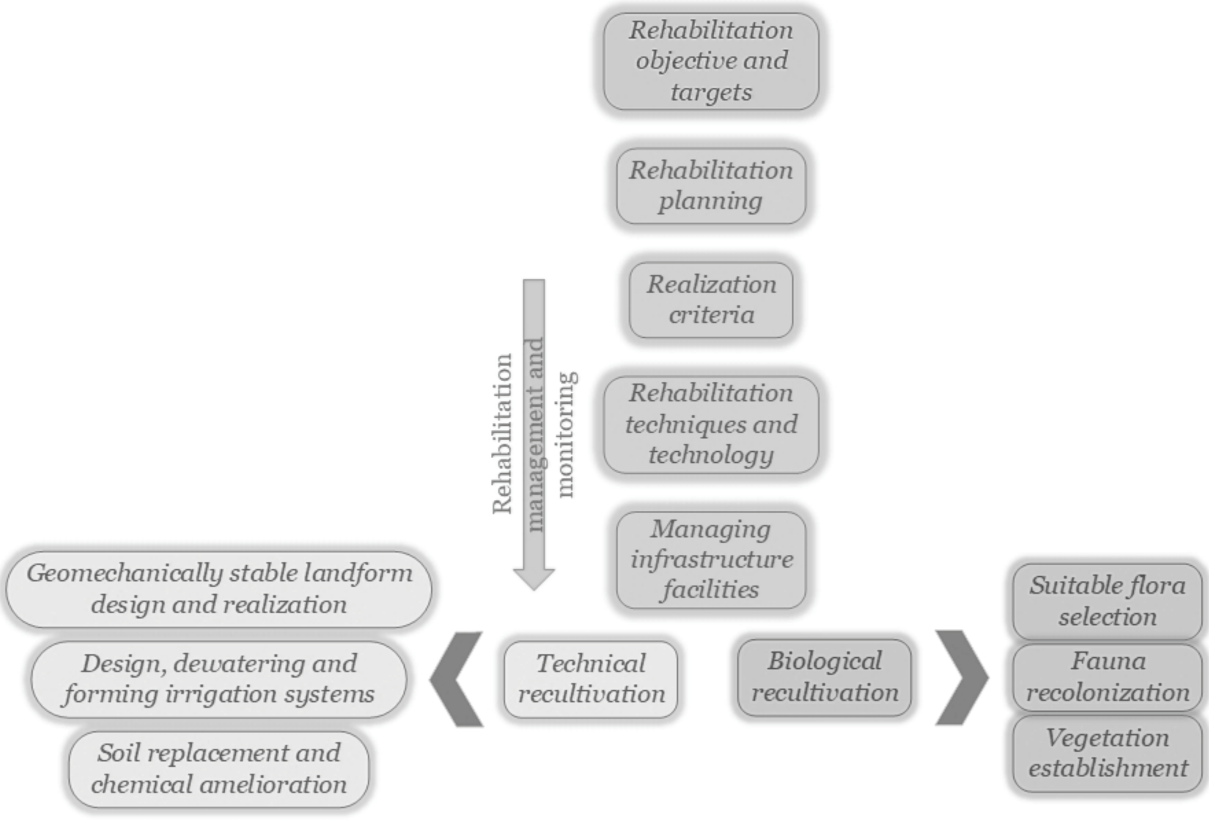

Figure 2. Phases of Rehabilitation Planning and Implementation

The goal of implementing the outlined phases of the rehabilitation plan is to re-establish the designed landscapes after mining, contributing to the long-term safety, health, and functional use of the area, in accordance with the social, economic, and environmental principles of sustainability (Figure 1).
The closure and rehabilitation plan with reclamation for opencast mines is a document prepared by the investor. It includes and describes all studies and plans related to the closure and reclamation of the site, as well as the relocation of all associated mining facilities. The plan covers geomechanical and chemical stability of the area and the potential future use of the land in the final pit limits of the opencast mine [4, 7]. It should

include alternative solutions with criteria for selecting rehabilitation implementation activities and long-term benefits for the local community.

There are three main stages in the development of the plan:

1. Preliminary Plan,
2. Interim Plans, and
3. Final Closure and Rehabilitation Plan.

In accordance with the international standard systems ISO 21795:2021 (Mine closure and reclamation planning), ISO 31000 (Risk management), and ISO 14000 (Environmental Management Systems), the core principles of rehabilitation planning include, among others:

- Continuous analysis and management of risks of failure in closure and reclamation plan elements, including risks to human health, safety, and the environment, as well as the evaluation of residual risks;
- Reducing flood risks through active surface water management;
- Improving water quality before discharge into rivers and streams, and promoting efficient use of collected water;
- Providing community benefits by creating more attractive and resilient places to live and work;
- Prioritizing solutions that enhance biodiversity and the quality of green spaces;
- Emphasizing long-term responsibility, stability, maintenance, efficiency, and monitoring.

2 Risks of Progressive Rehabilitation of Opencast Mines

Successful progressive rehabilitation is carried out throughout the entire life cycle of an opencast mine, up to its final closure. It includes ensuring the planned quality of work and the efficiency of simultaneous activities with mining. This leads to a reduction in long-term potential risks associated with the rehabilitated area and the occurrence of possible negative consequences, as well as undesirable environmental impacts after closure. In this way, through integrated planning, the financial resources needed for managing the impacts and risks related to opencast mining and long-term operations are reduced.

Risk assessment of rehabilitation includes risk and implementation option analyses for a given opencast mine location, ecosystem components, or conditions, in accordance with the ISO 31000 family of standards – Risk Management [2, 8]. It takes into account factors such as risk acceptability and sustainability, ecological and socio-economic impacts, benefits, and technical feasibility. The assessment forms the basis for risk management. A formal risk assessment of the implementation of the mine closure and rehabilitation plan should be conducted at the beginning of the opencast mine design process and each time the exploitation dynamics are updated, as well as for the final closure and reclamation of the mine. This assessment should identify the potential probability of rehabilitation process failures and the corresponding consequences.

During the operational phase of the mine, rehabilitation measures are used to eliminate or mitigate identified operational and latent environmental risks through timely corrective actions, along with oversight of the future land user. Integrated planning leads to optimal long-term landscape management after the end of mining, which aligns with the achieved land quality and the remaining and potential hidden environmental obligations related to the rehabilitated area. At the same time, sustainable rehabilitation is implemented by shortening the long-term financial, environmental, and social responsibilities of the mine for the abandoned exploitation area and its use after the opencast mine is closed (Figure 2).

3 Risk Evaluation of Rehabilitation

The most commonly used methodologies for risk assessment and evaluation are based on the interaction between the probability of a risk occurring and the consequences it may have on business activities, environmental protection processes, or the mine as a whole. Risk assessment includes the history of specific events and risk analysis (nature, frequency, consequences). For evaluating options related to the rehabilitation plan and sustainable land use as part of the opencast mine closure plan, risk models in the form of matrices are commonly used. These models provide a relatively quick and simple way to identify the best alternative for decision-making on preventive priorities that involve multiple criteria, in accordance with the ISO 31000 international standards system and the most commonly used qualitative FMECA method [9].

Matrix models are formed based on the estimated probability of rehabilitation risk occurrence and the losses resulting from process failure, using the adopted ranking criteria (*K*). In quantitative terms, according to the modified VFMECA method, risk (*R*) is, following the classical formula, the product of the probability of process failure (P_f) and the consequences (C_t) over time t_i ($i = 1, 2,\ldots, n$), which occur after the failure ($R = P_f * C_t$) (Table 1).

Table 1 *Risk matrix*

Consequences / Probability	(FMECA) Very low $K_1 = 1$ (VFMECA) $C_1 \leq 0.2$, M€	Low $K_2 = 2$ $C_2=(0.2\div0.4)$, M€	Medium $K_3 = 3$ $C_3=(0.4\div0.8)$, M€	High $K_4 = 4$ $C_4=(0.8\div1.5)$, M€	Very high $K_5 = 5$ $C_5 > 1.5$, M€
(FMECA) Very low $K_6 = 1$ (VFMECA) $P_f < 0.1$	VERY LOW RISK	VERY LOW RISK	LOW RISK	LOW RISK	MEDIUM RISK
Low $K_7 = 2$ $P_f = 0.1\div0.2$	VERY LOW RISK	LOW RISK	MEDIUM RISK	MEDIUM RISK	MEDIUM RISK
Medium $K_8 = 3$ $P_f = 0.2\div0.4$	LOW RISK	MEDIUM RISK	MEDIUM RISK	MEDIUM RISK	HIGH RISK
High $K_9 = 4$ $P_f = 0.4\div0.8$	LOW RISK	MEDIUM RISK	MEDIUM RISK	HIGH RISK	VERY HIGH RISK
Very high $K_{10} = 5$ $P_f > 0.8$	MEDIUM RISK	MEDIUM RISK	HIGH RISK	VERY HIGH RISK	VERY HIGH RISK

4 Cost Assessment of Rehabilitation or Reclamation and Consequences of Process Failure

The cost assessment of rehabilitation or reclamation and the consequences of process failure is carried out based on the opencast mine closure plan and must be regularly updated to reflect spatial and temporal changes under complex mining-geological and environmental conditions. Continuous monitoring of the mine closure process is also essential throughout all stages of rehabilitation and reclamation of the degraded area.
The estimation of losses due to delays in the rehabilitation project implementation is calculated using a well-known relation based on the present total monetary value of the consequence costs (C) at a critical selected time (t), with a discount rate (r), at the chosen time of analysis (t) [9]. The total cost (C_t) includes organizational and remediation expenses from the failure, plan renewal, production losses, and damage to reputation, environment, safety, and health, as shown in equation (1):

$$C_t = C \cdot (1 + r)^t \qquad (1)$$

After risk evaluation, priorities are established for implementing risk elimination or acceptable reduction based on the Risk Priority Number (RPN) in the FMECA qualitative method, where higher priority corresponds to a higher product of ranking coefficients (K). In the modified quantitative VMECA method, the Risk Priority Value (RPV) is used, where higher priority corresponds to a higher risk value [9]:

$$RPV = P_f \cdot C_t \qquad (2)$$

representing the absolute level (rank) of failure risk (Table 2).
Risk evaluation and the established priorities in potential preventive and corrective actions also lead to changes in the realization criteria of the rehabilitation plan, and influence the selection of appropriate rehabilitation techniques and technology, which significantly affects rehabilitation management and monitoring.

5 Rehabilitation of the External Waste Dump at the Drmno Opencast Mine

The active Drmno opencast coal mine is located in the western part of the Kostolac Basin, with an annual coal production of 9 Mt of coal. During the opening of the mine, an external waste dump was formed (Figure 3). Since progressive rehabilitation was not carried out during the phases of the preliminary and interim plans, it was only after the final formation of the external waste dump, with a flat surface area of around 2 Mm², that the final reclamation project included, and partially implemented, protective afforestation of the slopes and preparation of the flat surfaces for agricultural production.

Figure 3. Final Rehabilitation Plan of the External Waste Dump
(Left – Phase I, 2012): Initial rehabilitation plan (Center – Phase II, 2024): Wind Park implementation plan with locations of wind generators (Google image [10]) (Right – 2025): Installed wind generators

By 2015, through a slow-paced reclamation process, approximately 120 ha of dump slopes were afforested as a protective belt, while about 20 ha were experimentally improved and chemically-biologically reclaimed for the planting of rapeseed and alfalfa. Since it was proven that there is no risk of liquefaction on the well-stabilized dump, the remaining areas were subsequently designated for the construction of a Wind Park, including full infrastructure, which led to a general revision of the final rehabilitation plan.

By 2024, internal access roads and foundations for seven wind generators, each with a capacity of 3.3 MW, were constructed (Figure 3). Final works are being carried out in 2025. Reclamation of the dump, as part of the planned rehabilitation, is implemented in two distinct phases.

The first phase refers to the execution of the original mine closure and rehabilitation plan, while the second phase covers changes in the reclamation process resulting from the subsequent decision to build a Wind Park on the dump site, with planned completion by 2027.

Throughout the entire planned lifespan of the rehabilitation of the external dump, implementation risks remained high, with significant consequences and losses, primarily due to delays in execution and changes to the dump rehabilitation plan.

In accordance with the established risk evaluation methodology, a continuous rehabilitation risk assessment was conducted under subprocesses, determining the Risk Priority Number (RPN_FMECA), where higher priority corresponds to a higher product of ranking criteria related to the probability of failure and its consequences—and the Risk Priority Value (RPV_VFMECA), where higher, but also more accurate, numerical risk values are given greater priority (Tables 1 and 2).

***Table 2** Subprocesses risk evaluation and ranking by causes*

Subprocesses of rehabilitation process	P_f	C	RPN_{FMECA}	R_{VFMECA}	RPV_{VFMECA}
I Phase - External dump recultivation					
Geomechanically stable landform design and realization	0.4	1.60	**High risk (IV-K8*K5)**	0.64	**3**
Design and dewatering and irrigation systems forming	0.2	0.40	**Low risk (II-K7*K2)**	0.08	**7**
Reconstruction of the soil profile and chemical amelioration	0.2	1.97	**Medium risk (III-K8*K5)**	0.39	**5**
Selection of suitable flora	0.1	0.44	**Very low risk (I-K1*K8)**	0.05	**8**
Establishment of vegetation	0.4	2.34	**High risk (IV-K8*K5)**	0.94	**2**
Fauna recolonization	0.3	1.97	**High risk (IV-K8*K5)**	0.29	**6**
II Phase - Wind Park forming with external dump recultivation changes					
Construction of Wind Park infrastructure and recultivation changes	0.4	1.57	**High risk (IV-K8*K5)**	0.63	**4**
Wind Park starting operation	0.5	1.97	**Very high risk (V-K8*K9)**	1.99	**1**

Throughout the entire implementation of the rehabilitation plan for the external waste dump, continuous enhanced monitoring has been present, along with preventive corrective actions and necessary accompanying changes in rehabilitation techniques and technology.
According to Table 2, special attention has been focused on the geomechanical stability of the dump slopes, accelerating the commissioning of the Wind Park through completion of the infrastructure, establishment of vegetation, and reconstruction of the soil profile along with chemical amelioration.

Conclusion

Planning the progressive rehabilitation of opencast mine dumps is a continuous process and is crucial for identifying and undertaking the actions needed to ensure that the environmental management system (EMS) can achieve its intended outcomes. It supplements the influential elements of the EMS (in accordance with ISO 14000) to ensure its effective maintenance and improvement, especially in response to the frequent variability of inputs and outputs.
For this reason, progressive rehabilitation of the exploitation area during the mine's life cycle and closure process is today considered the most acceptable approach. It enables the timely identification of negative environmental impacts and the allocation of resources for their reduction or elimination in compliance with legal obligations.
It is essential that, through the development of a preliminary plan, interim plans, and the final mine closure and rehabilitation plan, the mining company defines sustainable processes and subprocesses, as well as criteria for risk evaluation and their consequences (in line with ISO 31000:2018 and ISO 21795:2021).
As an example, a comparative risk evaluation analysis of the implementation of the rehabilitation plan for the external waste dump of the Drmno opencast mine is presented. The assessment of priorities for implementing corrective and preventive measures to mitigate or eliminate risks is carried out using the conventional qualitative FMECA method and the quantitative VFMECA method, which is a modified version of the former in terms of risk quantification.
The analysis results indicate a sound developmental approach to sustainable rehabilitation planning, taking into account the specific requirements of the mining industry in the field of risk management. The modified VFMECA method eliminates or reduces certain noticeable shortcomings of the conventional FMECA method.

References

[1] A. Badri, S. Nadeau, and A. Gbodossou, A mining project is a field of risks: A systematic and preliminary portrait of mining risks, *International Journal of Safety and Security Engineering*, vol. 2, no. 2, pp. 145–166, 2012.
[2] BSI Standards Publication, *ISO 31000:2018 - Risk Management – Guidelines*, 2018.
[3] L. F. Contreras, An economic risk evaluation approach for pit slope optimization, *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 115, pp. 1–10, 2015.
[4] I. De Bruyn, A. Fourie, and D. Reid, Geotechnical considerations for the stability of open pit excavations at mine closure: Some scenarios, in *Mine Closure 2019*, Australian Centre for Geomechanics, Perth, 2019. ISBN: 978-0-9876389-3-9.
[5] ISO, *ISO 21795:2021 - Mine Closure and Reclamation Planning*, 2021.
[6] ISO, *ISO 14000 - Environmental Management Systems*.
[7] Australian Government - Department of Industry, Innovation and Science, *Mine Rehabilitation: Leading Practice Sustainable Development Program for the Mining Industry*, 2016. Available at: industry.gov.au
[8] N. Pavlović, B. Petrović, and T. Subaranović, Evaluation methodology of open pit mine overall slope failure risks, in *International Conference on Raw Materials and Circular Economy*, Athens, 2023.
[9] N. Pavlović, T. Subaranović, D. Ignjatović, and V. Pavlović, Compliance of FMEA and V-FMEA risk management methods in relation to the ISO 31000:2018 standard, in *14th International Symposium on Strategic Management (ISSCM)*, pp. 150–158, 2023. ISBN: 978-86-83497-30-0.
[10] Google Maps Imagery, Wind Park Drmno area satellite data, accessed in 2024.