



Article A Tunnel under an In-Pit Mine Waste Dump to Improve Environmental and Landscape Recovery of the Site

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Abstract: By adopting the green mining concept, the mining industry seeks to respond to the current societal objective of supplying the mineral raw materials necessary for economic development while minimising the ecological footprint. To accomplish environmental recovery simultaneously with mineral exploitation, as well as to take advantage of mine waste, this study proposes a new solution that includes the construction of a tunnel to access the mining area. The concept, developed with topographical and geological data, was tested for the Bled El Hadba phosphate deposit. The extraction volumes were estimated by considering all the technical and legal aspects of the exploitation. The results showed that the best location for the tunnel is on the non-mineralised bottom of the mine and placed after ore removal. The tunnel is then progressively covered by mine tailings as it is extended. This concept is applicable to sub-horizontal ore deposits. We show that the solution is feasible and allows full site recovery at the end of the open-pit mining phase.

Keywords: green mining; open-pit mining; ultimate pit limit; mining design; environmental recovery; landscape

1. Introduction

Although the European Union (EU) has had a strategy since 2008 for the sustainable supply of raw materials [1], either from global markets or through national production, in reality, the public strongly rejects mining for historical reasons. Resistance to mining is a global phenomenon, and the movements against mining are changing and adapting their discourse and strategy [2].

The causes of conflict vary and range from environmental impacts to socio-economic and health problems of the people who live near mines. Thus, despite the EU's efforts to increase self-supply, mining in Europe is unlikely to increase significantly, particularly in the most densely populated regions [3], without changes in public policies and technical and methodological approaches to mining projects. The response of companies through their 'corporate social responsibility' (CSR) programmes as mitigating measures [2] has shown itself to be globally insufficient.

The public's reaction is understandable since the extraction of minerals can affect soil quality, biodiversity, water resources, and the landscape, resulting in uninhabitable and visually unacceptable land [4,5]. To minimise these problems, in-pit dumping is often considered and used. Therefore, all the mining processes must be planned and controlled to identify potential problems and solve them in a timely way with appropriate measures. In short, the processes should be evaluated on an ongoing basis.

The production of mineral raw materials, particularly 'critical' minerals, both metallic and non-metallic, is fundamental for economic development and social well-being [6].



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). However, site rehabilitation is a critical practice for sustainable mining and a better relationship with local populations and society. The circular economy (CE) and green mining (GM) are concepts developed worldwide to support more sustainable industrial and social growth [7–9]. The GM concept has been introduced to improve efficiency and reduce the environmental impact of mining and can be categorised into seven different approaches: (i) the closure of illegal or non-compliant mines; (ii) the reconversion of ongoing mines; (iii) the development of options for environmentally friendly mining processes; (iv) the implementation of the latest green mining technologies; (v) the recovery of closed mines and respective surroundings; (vi) the re-evaluation of cut-off grades, and (vii) increased research and development in green mining technologies [10].

The accomplishment of environmental recovery simultaneously with exploitation, by taking advantage of the waste/tailings from the mine itself in an in-pit dumping process, contributes to the lessening of the impacts of mining. This step fits into the CE perspective and contributes to the EU's Green Deal from the first phase of extractive activity. However, this procedure, already common in many mines, can be further improved under certain conditions. That is, in addition to maintaining open-pit mining conditions, landscape and environmental recovery is improved and accelerated, and subsequent underground mining procedures are not restricted. Thus, this study proposes the construction of a tunnel under the tailings to access the active mining area. In order to test this new approach, a feasibility study on the implementation of the tunnel is carried out using, as an example, some basic data from a real mineral deposit, the phosphate deposit of Bled El Hadba. The great advantage of this solution is that it allows maximisation, at every moment of the recovered area since the tunnel replaces all the access ramps between the surface and the mining zone.

2. Materials and Methods

2.1. Site Characteristics

The phosphate site of Bled El Hadba is located at the eastern extremity of the Saharan Atlas in the Tebessa region of Algeria. The phosphate ore deposit is found in the Djebel Onk Basin, 14 km south-east of Bir El Ater and 14 km from the Djebel Onk treatment plant on the western side of the Djebel Zerga anticlinal structure, and about 6 km from the border between Algeria and Tunisia. It is close to other active mines (Djemi Djema and Kef Es Sennoun) discovered in 1873 [11]. Today, Algeria has reserves of 2.2 billion metric tons (3% of the world phosphate reserves), the fourth largest after Morocco (including western Sahara), China, and Egypt, and among the top five world reserves. Bled El Hadba alone has reserves of more than 800 million metric tons [12,13].

The deposit was characterised according to its geological and physical attributes, such as shape, dimension, continuity, position, dip, and thickness of the phosphate layers. With this general information, it was determined that the first approach to deposit exploitation should be through a strip-mining approach to minimise inter-contamination between the different layers.

The ultimate pit limit (UPL) was determined, and the block extraction sequence was defined [14–16]. The production schedule was not established because it was not important for the research objectives. This work also does not present a preliminary determination of the UPL for confidential reasons. However, this knowledge is also not necessary to present and understand the proof of the concept defined in the objectives.

For practical purposes, the UPL will be considered as 100 m but, with this approach, the transition from open-pit to underground mining can be carried out at any time. As a proof of concept, and once the exploitation/recovery cycles are repeated independently from depth until the UPL is achieved, the elements made available are sufficient to demonstrate the solution and its technical feasibility.

2.2. Site Exploration

The research was carried out in different steps. In the first step, the geological and topographical data and the legal mining standards of the Algerian deposits were extensively analysed [14], seeking to establish the inputs, outputs, and processes constituting the problem. The geological structure of the Bled El Hadba zone (Figures 1 and 2) [13] shows that Thanetian phosphate forms a NE–SW-oriented outcropping strip that sinks westward under the silex Ypresian limestone of the Miocene sand [15].



422800 423000 423200 423400 423600 423800 424000

Figure 1. Geological map of the structure of the Bled El Hadba phosphate deposit in Algeria.



Figure 2. Geological Profile III oriented east-west.

The Bled El Hadba phosphate deposit is composed of three main layers (Figure 2) whose average thickness is as follows: a 6 m deep lower (basal) layer of phosphate, deficient in phosphorus pentoxide (P_2O_5) and very dolomitic; a 16 m principal layer of phosphate, rich in P_2O_5 and not very dolomitic; and a 7 m top layer of phosphate, deficient in P_2O_5 and very dolomitic [15].

The stripping ratio (waste/ore) of the deposit was determined by the geological and mining research office (BRGM) to be 1.6. According to the available data [16], the compression resistance of phosphate is about 219 Kg/cm² = 21.47 MPa and of phosphatic limestone about 311 Kg/cm² = 30.49 MPa.

Data from 45 fully georeferenced surveys with x, y, and z coordinates were obtained and combined for processing. These elements were then introduced into the topographical plan (Figures 1 and 2) to allow proper project development.

2.3. Mine Design

As previously stated, given the shape of the deposit, the mining project was designed according to the strip-mining approach, with recovery of the abandoned areas immediately with the rejected mined materials.

Figure 3 shows the extraction order sequences of phase 1. The exploitation strip sequences according to mine parameters (bench height, platform length, and the roads to all the platforms) are shown in Figure 4, and were defined and designed to extract only one ore layer per bench, avoiding contamination of the ore by the sterile layers and, consequently, minimising the costs of transport and treatment in the ore concentration plant; define efficient transportation routes inside the mine; and build an infrastructure that allows future underground exploitation after it is no longer economically feasible to proceed with open-pit mining.



Figure 3. Sequencing of bloc extraction in the first exploitation phase. Two blocks with the same number mean that they are exploited at the same time.



Figure 4. The first phase of exploitation with environmental recovery showing the conveyor belt location.

The mine parameters (bench height, slope, and platform length) were selected according to Algerian mining legislation; the maximum bench height is usually about 15 m for rock and 5 m for sand, for the safety of the mine as well as of the workers. The need to exploit each of the ore layers with a different bench was considered a restriction. This entails analysing distinct procedures for extraction, loading, and transportation to ensure the best operational performance on each court due to its different characteristics. For planning purposes, platforms with lengths ranging from 25 m to 75 m were considered. These values were determined according to the deposit's features, the sequences defined for exploitation, the chosen equipment for the extraction, and the loading and transportation procedures in open-pit operations. The slope of the designed benches was about 15°.

For the road design, a minimum width of 20 m was used, based on the circulation of dumpers 5 m to 7 m (100 t to 150 t) in width. Slopes less than 8%, tending to value around 5% or 6%, were projected. In the exploitation phase, the project designed access to the entire mine throughout its life cycle, with links to the regional road system of Tebessa city to allow for the transportation of ore to the processing plant. The width of the roads was about 10 m, with a projected slope less than 10% on the benches. These values were intended to improve circulation and minimise the energy consumption of dumpers (on rock platforms) and articulated dumpers (on sand platforms).

The location of the first waste dump was selected based on the unevenness of the surface to minimise the occupied area (Figure 5). A higher elevation site was chosen because when performing recovery later, it makes it easier to push the wastes from the external dump into the pit. This location was less time-consuming and, consequently, more economical, and reduced transportation costs during pit recovery. The necessary area for the external waste dump was calculated based on the volume of the different materials (phosphate, gypsum, limestone, and sand). The removed materials were assumed to be stored separately; this included the removed plant species (mainly cactus and apple trees), which were replanted during environmental recovery.



Figure 5. Final profile—III—of environmental recovery showing the layers and the tunnel built over the conveyor belt.

The workbenches were connected to the benches of the internal dump, which allowed faster and cheaper environmental recovery of the site; in Figures 2 and 5, yellow represents the sand, orange the limestone, brown the marl, and grey the phosphate benches.

For extraction, a tunnel was designed to be built under the heap on the base rock at the deposit bottom. The construction of this infrastructure has multiple advantages: it allows (i) channelling of all extracted ore and the debris which cannot be stored inside the mine; (ii) the simultaneous recovery of the already mined area, minimising the extent of exposed pit; (iii) the acceleration of environmental recovery; (iv) the minimisation of the impact on the landscape; (v) the shift from open-pit mining to underground exploitation at any time, and (vi) the reduction in transport costs by replacing dumpers (whose energy consumption is high, particularly when going up a ramp) with electrically driven conveyor belts.

A conveyor belt was designed in 100 m sections, with a maximum expected slope of 20% [17], to go through the tunnel.



Figures 5 and 6 show the projected site after completing open-pit exploitation, with the location of the tunnel for possible future underground exploitation.

Figure 6. The final phase of environmental recovery showing the infrastructure (tunnel) built over the conveyor belt.

The volumes to be removed from each layer were determined based on the mine design, taking into account the number of blocks (strips) in each layer and the average height and surface area of each block. In the Bled el Hadba deposit, the overall volume of the pit includes the volume of clay, limestone, and sand.

The main part of the wet residues of the plant was assumed to seep into the dump and serve to cement the particles of the remaining waste material.

Based on these elements and the swell factor [18], was concluded that it was feasible to recover the site based on the sterile layers and the treatment plant's tailings. With these materials and proper planning, it is possible to rebuild a landscape similar to the one before mining began.

These results will be compared and discussed to verify the circumstances in which the waste materials produced are enough to fill the space opened by the mining operation [19].

3. Results of Open-Pit Recovery

Tables 1 and 2 present the results of the calculations; those for the different layers were performed based on three exploitation zones and their geologically representative cuts.

Profile I									
Layer	Total Bench Height of Each Layer (m)	Area (m ²)	Volume (m ³)						
Sand and clay	38	386,359	14,681,642						
Limestone and gypseous marl	8	278,520	2,228,160						
Phosphate (top layer)	8	331,612	2,652,896						
Limestone and gypseous marl	21	498,611	10,470,831						
Phosphate (main layer)	30	543,871	16,316,130						
Marl	2	534,474	1,068,948						
Phosphate (lower layer)	Phosphate (lower layer) 3								
Profile II									
Sand and clay	22	112,998	2,485,956						
Limestone and gypseous marl	14	156,635	2,192,890						
Phosphate (top layer)	29	187,723	5,443,967						
Limestone and gypseous marl	15	327,645	4,914,675						
Phosphate (main layer)	15	325,154	4,877,310						
Marl	3	395,696	1,187,088						
Phosphate (lower layer)	Phosphate (lower layer) 1		385,010						
Profile III									
Sand and clay	22	103,765	1,867,770						
Limestone and gypseous marl	22	287,407	6,322,954						
Phosphate (top layer)	6	305,378	1,832,268						
Limestone and gypseous marl	17	436,796	7,425,532						
Phosphate (main layer)	30	539,932	16,197,960						
Marl	2	541,627	1,083,254						
Phosphate (lower layer) 3		537,538	1,612,614						

Table 1. The volume removed from the different layers in profiles I, II and III.

Table 2. Comparison of the extraction wastes with the original surface level of the exploited area.

Material	Total Volume Extracted from the Pit (m ³)Swell Factor		Total Volume after Fragmentation (m ³)					
Marl	3,339,290	1.25	4,174,113					
Limestone and gypseous marl (m ³)	33,555,042	1.375	50,332,563					
Sand and clay (m ³)	19,035,368	1.2	22,842,442					
Phosphate (m ³)	50,892,774	1.5	-					
Total	106,822,474	-	73,154,737					
Comparison with the Original Surface Level								
The difference between total volumes (m ³)		33,667,737	-					
Total exploited area (m ²)		1,743,166 -						
The difference from the original surface level (m)		-19.3	-					

4. Discussion

4.1. Advantages and Limitations of Tunnels

Transportation is one of the most significant contributors to the financial costs of mining, as well as being one of the factors with the highest impact on the environment. Shovels and dump trucks are usually used in the surface extractive industry, with diesel as the primary energy source. A trucking transportation system is the easiest to design and plan for when a mining project starts [20]. However, this solution is not the most economical compared to continuous conveyor belts. It is possible to reduce approximately 50% of fuel, lubrication, and tire consumption costs, which depend on the cost and the availability of oil products, with the use of conveyor belts. A model was developed by Bajany et al. [21] to determine the best shovel allocation to minimise the fuel consumption of dump trucks and shovels during haulage. In-pit conveying systems have been advancing for many decades [22] and highlight the increase in mining profitability and production efficiency.

The transition to underground mining is sometimes feasible. However, it is a complicated and expensive task which requires careful planning [23,24]. Consequently, consideration of all these aspects is essential when designing projects. To overcome the challenges of transportation—technical and especially economic difficulties—the construction of a tunnel under the heap and removal of ore using a conveyor belt was proposed.

The implementation of an in-pit conveyor at an early stage of the mine project has been tested and demonstrated to be the most cost-effective option with lower carbon emissions [25]; emissions were shown to increase when using a large number of trucks. Therefore, the proposed alternative transportation will reduce the number of trucks needed, leading to a decrease in carbon emissions. Moreover, conveyors have a longer life and throughput than trucks.

In the case of occupational safety [26], most accidents in the mining industry occur during the operation, especially maintenance, of transportation equipment, such as haulage trucks and dumpers. Osanloo and Paricheh showed that decreasing the number of trucks on site will reduce traffic volume and eventually decrease fatalities, as more than 90% of fatal accidents occur due to incidents related to trucks [17]. The same study also reported the efficiency of the in-pit conveyor haulage system (IPCS) compared to the truck haulage system (TS) for mines with a high production rate, as well as significant cost reductions when applied correctly. In addition, the use of clean technologies in mining should increase due to the new guidelines that support sustainable development as required by the United Nations. These legislation and regulations would control carbon emissions with a view to slowing down global warming. Therefore, it is necessary for the mining industry to adopt innovative solutions to reduce energy consumption and generate less greenhouse gas emissions [22]. The transition to a low-carbon economy, by using low-emission technologies such as clean electric transportation systems, can lead to a climate-resilient future. The greenhouse gas emissions of IPCS and TS have been calculated and compared [27], and the results showed a potential reduction with IPCS, especially when using electricity generated from natural gas rather than from black coal. In the case of transportation, the energy consumption of diesel trucks is higher, and consequently their CO_2 emission is higher, than that of power-driven conveyor belts [28]. The conveyor belt performs better than truck haulage in saving energy and reducing greenhouse gas emissions. This provides solid support for the proposal to replace oil products with electricity in the mining industry. In this study, low-emission and low-cost transportation was used as the main factor for determining the method and equipment used in the mining operation. This alternative will allow the mine's transition from open-pit to underground without changing the project plan.

However, tunnels also have some drawbacks. Firstly, they are not a universal solution that can be used as a standard for all open-pit mines. This solution is restricted to deposits with specific configurations; the one presented in this study as an example is particularly favourable. According to the needs, there are also technical specifications, such as mechanical resistance to the load induced by the heap and tunnel section dimensions. Prevention techniques will also have to be considered; namely those related to possible shocks caused by the discharge of blocks in the upper part of the heap. Additional costs of the construction and maintenance of the structure must also be considered.

4.2. Environmental Recovery

The comparison between the volumes of generated wastes and the total amount of material removed from the pit showed a significant difference between the total volume removed and the volume of sterile material. This confirms that while phosphate mining generates many different types of waste, environmental recovery cannot be undertaken with the original topography. Several solutions can be considered for this problem. The most obvious solution is to use the volume of tailings produced by the processing plant in the first place and the wastes produced in underground mining procedures in the second place.

In this study, the volume of tailings from the processing plant was calculated by considering the functional performance of each of the phases: screening, dry treatment, and wet treatment. The phosphate volumes after screening, the amount treated by each processing method, the volumes of concentrated phosphate, the rejects of each phase, and the total rejects of the treatment plant are shown in Table 3.

Table 3. Comparison with the original surface level of the exploited area and the tailings of the processing plant.

Phosphate Processing Phases	Amount of Phosphate in Each Phase (%)	Performance of Each Phase (%)	Amount of Phosphate in Each Phase (m ³)	Output of the Processing Plant (m ³)	Rejects of Each Operation (m ³)	Phosphate Swell Factor of Rejects (m ³)			
Screening after fragmentation	100	95	50,892,774	48,348,135	-	-			
Rejects of the screening			-	-	2,544,639	3,816,958			
Dry enrichment	50	61	24,174,068	14,746,181	9,427,886	14,141,830			
Wet enrichment	50	70	24,174,068	16,921,847	7,252,220	10,878,330			
Total (m ³)	-	-	-	31,668,029	19,224,745	28,837,118			
Comparison with the Original Surface Level Considering the Tailings									
The total volume removed from the pit (m ³)			106,822,474	-	-				
The volume of waste including the tailings (m^3)			101,991,855	-					
The difference between volumes (m ³)			4,830,619	-					
Total exploited area (m ²)			1,743,166						
The mean difference from the original surface level (m)			-2.77		-				

The fragmented phosphate is sent to the screening operation before dry and wet enrichment. The input of each type is shown in Table 3. The output of each operation was also estimated using a standard recovery value for this type of ore to find the volume of the rejects by the swell factor considered to improve pit recovery.

The amount of waste including the total volume of tailings from the processing plant was still less than the pit volume, but the difference was slight. Therefore, the ground surface level will be lower than the original surface level by about 2.77 m on average. With this average reduction in the final level of the space occupied by the pit, it is possible to model the terrain perfectly framed in the landscape, without affecting the natural runoff of rainwater. Mine dumpers can transport dry tailings on return from the processing plant, while wet tailings can be pumped through pipelines.

The results of this study show that by transporting the waste generated in the processing plant to the in-pit pile, it is possible to avoid the construction of a specific waste dump for these products, and as a consequence, improve the quality of the recovered landscape. The dry tailings can increase the surface level, and the wet tailings can facilitate greater compaction of the landfill by acting as a cement.

5. Conclusions

5.1. General Conclusions

Based on real data, this study aimed to demonstrate the technical feasibility of simultaneously carrying out three operations: (1) open-pit mining; (2) landscape and environmental recovery, and (3) the creation of conditions to start underground mining at any time.

From the results of this study, it can be concluded that it is possible to simultaneously exploit the mine and carry out environmental recovery, using a temporary external dump during a short transitional period at the beginning of the exploitation; to use all the tailings generated by the processing plant to fill the pit and improve the final results of landscape recovery; to have a separate bench for each material, increasing extraction efficiency; to create conditions to start underground exploitation at any time by building a tunnel under the dump as mining progresses; and to employ the same basic infrastructure for both

open-pit and underground exploitation by extracting the ore through the tunnel using a conveyor belt.

This study presents a feasible solution for managing the removed volumes—a difficult problem for mining. Although the study is based on a specific type of deposit, it is clear that the proposed approach could be applied to any other similar deposit.

5.2. Future Work

This study opens the doors to other investigations in different mining areas, such as mining design to avoid changing the global extraction infrastructure each time the UPL is altered; location and design of the dumps inside the open-pit mines to improve the stability of the slopes and workers' safety conditions; characterisation and location control of the materials to improve dump stability and facilitate their possible future re-mining, and techno-economic feasibility studies to understand whether the deposit is economically exploitable underground by considering the different costs of extraction, transportation, and treatment, as well as the marketable price of the mineral to be exploited.

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