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Application of the attainable region method to determine optimal conditions for milling and leaching

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ABSTRACT

In this work, we apply the attainable region (AR) method to laboratory data in order to optimize the milling and leaching processes of a low grade gold ore. To date, no research has been published on the application of the AR optimization technique on combined milling and leaching processes. The advantage of the AR approach lies in its ability to simplify the optimization problem, as searching over a defined space for the maximum of an objective function is a fairly standard procedure. The objective function we selected in this investigation was that of optimizing a linear function of the value of the recovered material minus the cost of both milling and leaching. Using the three variables (milling time, leaching time and recovery), we constructed a 3D plot and used it to obtain all the possible recoveries from the different milling and leaching times. The optimum for our chosen objective was then found by overlaying a contour plot of the objective function on the 3D plot. Our results show that the optimum was obtained at 90% recovery with a profit value of \$600, milling time of 30 min and a leaching time of 1750 min.

1. Introduction

African countries are facing a general increase in demand for electrical power. In South Africa, the demand is now surpassing the supply from the Electricity Supply Commission (ESKOM). This has resulted in load shedding strategies being implemented in many local communities in an attempt by the country's energy provider to cope with the high demand. Perhaps, a better approach is for ESKOM to propose use of energy efficient technologies in the country's largest power consuming industry; the mineral processing sector.

1.1. The milling process

In mineral processing, the milling unit operation is the highest consumer of energy. The objective of carrying out milling is not merely to reduce the particle size of the feed material, but also to liberate the constituent minerals that make up an ore. This is done so that valuable minerals can be separated from the gangue, in downstream processes, such as leaching. However, the milling process is generally performed relatively poorly, and at a considerable expense in terms of electrical power utilization. Tomanec and Milovanovic [1] estimated that milling accounts for more than 50% of the total power used in the concentration process, but this can rise to as high as 70% for hard or finely dispersed and inter-grown ores. Apart from being relatively wasteful of energy, the milling process is also inefficient with regard to mineral liberation because of the indiscriminate nature of the grinding force.

The efficient liberation of minerals remains one of the major challenges in treating low grade ores due to the large volumes of run-of mine that has to be processed. The grain sizes of these ores also poses further challenges, as they require ultra-fine milling in order to achieve the desired degree of liberation [2]. Regrettably, ultrafine milling has led to higher energy utilization, because both the mineral and gangue components are indiscriminately milled. Due to the high costs associated with milling to fine particle size classes, a number of researchers have been coming up with strategies [3,4,5,6,7] and designs [8,9,10,11,12] meant to reduce energy consumption and hence costs.

1.2. The leaching process

In leaching, an ore is brought into contact with a liquid phase, so that the values in the ore are removed by dissolving them from the solid into the liquid phase. Over the years, the use of reagents for extraction of minerals from ores has been the major treatment method and has proved to be very effective in the extraction of different ores. The right amount of the reagent under the right conditions should be applied to the process especially if the lixiviant is unstable or harmful. Excessive

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use will increase the overall cost and reduce the efficiency of the leaching process.

It is therefore of paramount importance that the study of milling and leaching processes are given much attention by researchers. We have not encountered a model or method that can predict or optimize both the milling and leaching processes simultaneously. In this work, we apply a model free technique known as the attainable region (AR) method to optimize the milling and leaching processes of a low grade gold ore.

2. Theoretical background

2.1. The milling and leaching processes

The main objective of any mineral processing operation is to realize a profit. The challenge is on mineral researchers to come up with strategies that reduce costs through plant and circuit optimization, in order to increase profit. If one is to optimize the milling stage, the downstream leaching unit process should be studied in terms of the required particle size or degree of liberation. Fine grinding from the milling process leads to high leaching reagent costs and on the other hand coarse milling gives result to low recoveries. The rationale behind this is that one does not get an optimum solution by optimizing a single unit operation in a sequence of unit operations and therefore it is necessary that the overall system is optimized.

The total milling costs are made up of grinding media, liner and energy costs. In ball milling, the effect of the grinding media plays a significant role in the determination of the milling costs. One can reduce these costs considerably by merely improving the efficiency of the ball impacts inside the mill. The impacts are influenced by the design of liners as well as the type of discharge mechanism. Improving the efficiency of the grinding media impacts translates into reduced liner and grinding media wear rates as the balls get more involved in impacts that result in size reduction of the feed material, as opposed to ball-ball or ball-liner impacts.

Most of the gold produced in the world is extracted from gold ores by the cyanide leaching process. The ore is first ground to expose the gold carriers and the milled material is then reacted with an oxygenated cyanide solution that dissolves the gold, leaving solid gangue minerals that are disposed of. The effect of particle size reduction and liberation on gold recovery therefore plays a major role in the gold leaching process. Most reported studies indicate that gold recovery increases with increase in fineness of the mill product [13]. While it is acceptable that a finer size distribution is favorable in order to increase gold recovery by leaching, the benefits of the increased recovery could be offset by higher grinding costs and cyanide consumption [3].

Studies done by Stange [14] on capital (CAPEX) and operation (OPEX) costs associated with leaching, showed that labour, ball milling, reagents and chemicals contribute a high percentage to the overall cost for the process. Therefore when one is to consider optimizing both the milling and leaching processes, a trade-off must be struck in terms of degree of liberation or optimum particle size and recovery, so that both CAPEX and OPEX are kept minimal.

2.2. The attainable region (AR) approach

The history of the AR method goes back to 1964, when Horn [15] found a way to address the problem of defining an optimal reactor structure by noting that for given kinetics and feeds it is likely to find the set of all possible output concentrations from all possible reactor systems. Horn then called the set of all possible outputs the AR. Once the area of the AR has been established and represented in a diagram, it is possible to search over the boundary of the region to identify the output parameters that maximize an objective function. The advantages of this approach lies in its capacity to simplify the optimization problem, as searching over a defined space for the maximum of an objective function is a fairly standard procedure. The AR approach can also make use of an objective function to set a target against which designers and operators of milling circuits can measure the success of a specific process.

Horn and other researchers who followed up on his proposal were unable to discover a systematic method of finding the AR, until Glasser et al. [16] re-examined their seminal idea. They then approached the problem of constructing the AR from a different perspective, looking at the fundamental processes occurring in a process rather than at the equipment used. Having identified the AR, they were able to obtain the maximum potential of a given objective function, and then specify the maximum value for that function.

In order for one to apply the AR technique, the first step is to choose a fundamental process, for example comminution, flotation, or leaching. The second step is to select the state variables which characterize the output state of the system. Typically these would include concentration, mass fractions, reaction conversion or recovery. The third step is to construct a candidate AR. The final stage is to find a point in the AR at which the process is optimized. This normally occurs on the boundary of the AR plot.

Studying this method and understanding the approach, has been the interest of many researchers in the field of mineral processing. Khumalo et al. [17] applied the approach to comminution and focused on achieving a desired product with optimal use of energy during the milling process. Metzger et al. [18] used the AR approach to optimize particle breakage in a ball mill. Chimwani et al. [19] applied the AR method to determine an optimum ball size distribution for the maximum production of a narrowly-sized mill product. Danha et al. [20] applied the technique to identify ways of improving the milling efficiency of a platinum ore. Hlabangana et al. [21] used the method to determine major trends and optimize particle breakage in a laboratory mill. This is a summary of some of the research done using this powerful tool.

The work reported here extends on how we can apply this model free tool to a milling and leaching process in order to optimize the cost, recovery and time of operation. It is not intended to set out ideal operating parameters for the mineral processing industry, but aims to show how the AR technique can be used to develop some ways of improving overall performance and recovery.

3. Material and methods

We obtained a run-of-mine sample from a small scale gold mine situated in the Carletonville area of Johannesburg, South Africa. Table 1 shows the composition of the low grade gold ore which was determined by X-ray fluorescence (XRF) giving the phases available and also showing whether any variations are present which might affect

Table 1
XRF analysis for the low grade gold ore.

XRF analysis	
Phase	Composition (%)
SiO_2	73.5
Al_2O_3	12.8
Fe_2O_3	5.45
MnO	0.05
MgO	3.85
CaO	1.21
Na_2O	0.43
K_2O	1.45
P_2O_5	0.05
Cr_2O_3	0.04
SO_3	0.23
S	0.64
CuO	<0.01
Total	99.71