SYSTEMATIC DIAGNOSIS OF FLOTATION CIRCUIT PERFORMANCE BASED ON PROCESS MINERALOGICAL METHODS

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ABSTRACT: Operators of industrial flotation circuits experience every now and then situations where the processing performance of the plant is poorer than expected. Usually this leads to a continual and useless debate whether the problems are related to the ore properties or to the process. This paper presents a systematic approach to problem diagnosis using an analysis method based on process mineralogical tools. The diagnosis first requires a base-case analysis where the key process streams of the circuit have been sampled and studied by applying mineral process simulation in combination with the particle tracking technique, i.e. by balancing mixed particles of different mineral composition. This creates the base model of the flotation process against which the deviations are compared. Common performance problems are divided in three groups, which refer to recovery, grade and impurity. The mineralogical reason can in each case be a change in (i) mineral assemblage, (ii) head grade, (iii) liberation degree, or (iv) mineral associations. The diagnosis progresses by classifying the indications and by ruling out causes by means of process mineralogical methods. The procedure is presented as a diagnosis chart with suggestions for how to cure the problem. To illustrate the application of the method several practical examples are presented.

1. INTRODUCTION

From time to time industrial flotation circuits show processing performance poorer than expected. Problems refer to capacity, recovery and grade of the concentrate. For a given plant throughput the following problem cases can be distinguished, compare (Figure 1):

I. Pure recovery problem: Decrease in recovery, concentrate grade remains the same.
II. Combined grade and recovery problem: Grade and recovery below the operating point for the base case.
III. Pure concentrate grade problem: Grade below reference point, same or higher recovery
IV. Improved process performance (requires economic evaluation)
V. Recovery problem due to quality giveaway.

Common process control solutions to solve these problems refer to adjusting flotation air flow rate, changing froth depth, regulating reagent dosage or steering throughput to increase flotation times, e.g. [Maldonado et al., 2012] [Remes, 2012].

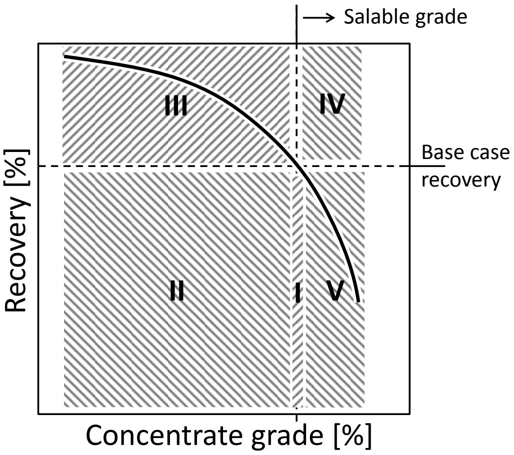


Figure 1: Grade-recovery trade-off (curve describing the base case).

But these measures are not always successful due to changes in the mineralogy of the plant feed. Then a more detailed analysis is needed. The diagnosis approach presented in the following is based on the assumption that problems related to non-optimal settings of the process control parameters, e.g. grade problems from too high or recovery problems from too low collector/ depressant dosing, frother dosing related recovery problems, combined grade and/or recovery problems from air rate or froth depth etc., have already been sorted out.

2. PROCESS MINERALOGICAL DIAGNOSIS APPROACH

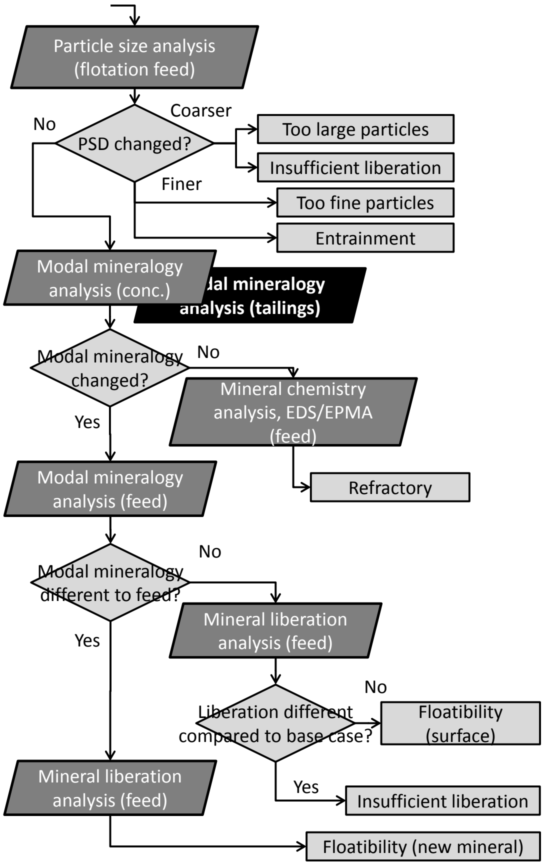


Figure 2: Diagnosis chart for grade problems (with alternative in black for recovery problems).

(Figure 2) shows the diagnosis chart for identifying the reasons for concentrate grade and recovery problems related to the mineralogy.

Starting from the analysis of the base case as the reference for process performance, the actual flotation concentrate or the tailings, respectively, is examined. The different analysis types used in the different steps comprise:

- Particle size analysis, usually by sieve analysis and/or laser diffraction.
- Chemical analyses, i.e. assaying using wet chemical analyses or spectroscopic techniques as X-ray fluorescence (XRF), atomic absorption spectroscopy (AAS), inductively coupled plasma (ICP) etc.
- Mineralogical analyses for the identification of mineral phases, e.g. by using microscopy (optical or electron), X-ray powder diffraction (XRD) or scanning electron microscopy (SEM), and for determining the chemical composition of minerals by SEM equipped with energy or wavelength dispersive spectrometry (EDS and WDS).

Modal mineralogy (phase composition data) can be determined from either image analysis, XRD (using Rietveld refinement) or by element to mineral conversion, i.e. converting elemental composition into mineral composition using numerical routines, e.g. [Lund et al., 2013].

The above-mentioned analyses are conducted on bulk level. For a more detailed mineralogical characterisation other analyses are required that are applied on a size by size basis in order to determine mineral assemblage and modal mineralogy, mineral associations and liberation degree, as well as texture information for the individual size fractions. For such a quantitative mineralogy analysis advanced and efficient systems for “automated” mineralogy are nowadays applied that make use of electron beam-based techniques:

- MLA [Fandrich et al., 2007]
- QEMSCAN [Sutherland and Gottlieb, 1991]
- INCA Mineral [Liipo et al., 2012]

The detailed analysis gives further indications with respect to answering the question whether performance problems have mineralogy related reasons or depend on suboptimal process control schemes.

After every analysis step decisions are taken in order to identify the next step in the procedure and finally arrive at a diagnosis. The successive increase in information allows narrowing the potential reasons and paving the way for curing the performance problem using for instance the following measures:

- Measures to reduce the fineness of grind (e.g. by reducing throughput) in case of too large particles for flotation or insufficient liberation.
- Change of flotation chemistry in case of modal changes or changed floatability, i.e. changed surface properties due to oxidation.
- Blending or additional downstream processing (e.g. leaching) in case of refractory problems.

It can also become necessary to re-evaluate the process economy, e.g. if recovery cannot be improved by further grinding, or if penalties have to be accepted.

3. TESTING THE CONCEPT WITH A SERIOUS GAME

To evaluate the diagnosis method described above in operational practice would require a long-term systematic testing. Even so, the nature of the problems experienced in a single concentrator could be quite limited. Therefore the method has been tested using a serious game.

The game was originally developed in 2011 for an advanced level Geometallurgy course at Luleå University of Technology. At that time the game scenarios were built using a process simulator but the user interface was not computerized. Instead the procedure worked manually and the analysis results after each request were given on a piece of paper. In 2012 the interface was changed to special built software that records all the actions made by the users enabling an analysis and evaluation of different problem solving strategies used by the students. The game has been conducted at four different universities within five different university courses.

3.1. Description of a Serious Game: Adventures of a Process Mineralogist

The game is based on detailed process simulations built up by using base case surveys. Within this analysis the key process streams of the flotation circuit under consideration are sampled and then analysed. Sampling is complemented by evaluation of the simultaneously recorded operational data, i.e. mass or volume flow, and solids concentration.

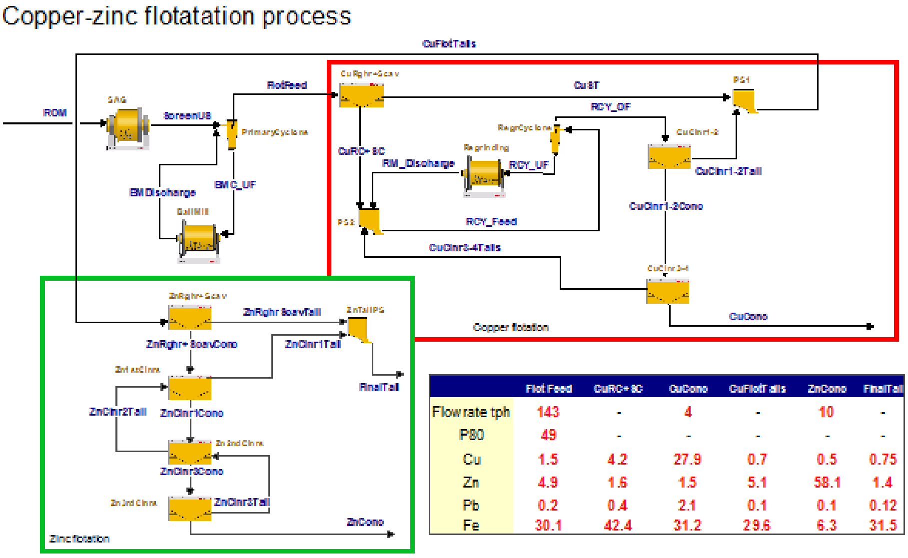
Data reconciliation techniques are applied in order to minimize errors by determining those flow values and composition data that fulfil the material balances in each point of the flow sheet with the least error. From the set of material balances already a basic evaluation of the process performance and an identification of potential performance problems can be conducted when calculating grades and recoveries of the valuable minerals in each product stream as well as mineral losses to tailings and impurities in the concentrates.

The picture received from this analysis is a snapshot of the plant performance for a given feed and a certain setting of the process control parameters. From the material balances already simple process models for the flotation units can be formulated but this cannot answer to questions on the expected performance if the plant feed is changing. If for example head grade, mineral assemblage, grain size of the minerals, association of the valuable mineral, or degree of liberation differ from the base case, the validity of the model will be limited.

This problem can be solved by developing a process model that is capable of forecasting the metallurgical performance of the circuit even if the plant feed is changing. Also relevant operating parameters like for instance air flow rate and froth depth have to be considered. Flotation models that are suited to fulfil these requirements are basically kinetic models. For forecasting the metallurgical performance of a flotation circuit considering significant changes in the textural attributes of the processed ore these flotation process models have to be extended to the particles and mineral liberation level.

For the reconciliation of multiphase liberation information two techniques exists: one developed by Gay using probability methods [Gay, 2004] [Gay and Vianna, 2002], and another using simple multiphase particle classification, called Particle Tracking, developed by Lamberg and Vianna [Lamberg and Vianna, 2007]. The latter is a full mass balancing-modelling-simulation concept starting from analysis guidelines, via extrapolation technique for generating liberation data even for size fractions not analysed, through to multiphase particle balance and simulation, as the stream information from the Particle Tracking can directly be used in the process simulator HSC Chemistry [Lamberg and Tommiska, 2009] [Roine, 2009].

The circuit demonstrated here is the Çayeli Cu-Zn flotation circuit which was surveyed by an Amira P9 project [Ergün et al, 2005a] [Ergün et al., 2005b]. Based on the mass balancing on liberation level a simulation model was established using the Sim module of HSC Chemistry 7.1, compare (Figure 3).



	Flot Feed	CuRC+SC	CuConc	CuFlotTails	ZnConc	FinalTail
Flow rate tph	143	-	4	-	10	-
P80	49	-	-	-	-	-
Cu	1.5	4.2	27.9	0.7	0.5	0.75
Zn	4.9	1.6	1.5	5.1	58.1	1.4
Pb	0.2	0.4	2.1	0.1	0.1	0.12
Fe	30.1	42.4	31.2	29.6	6.3	31.5

Figure 3: Simplified Çayeli flotation circuit used in testing with the serious game. Table in lower right corner is the standard report of the metallurgical performance as given in each case for the players.

The particle-level flotation model used here is the so-called Amira P9 model [Runge et al., 2003] where the floatability is given for fully liberated particles and for composite multiphase particles a weighted average based on the minerals present in a particle is used. For determining the floatability of fully liberated particles the Particle Tracking technique [Lamberg and Vianna, 2004] was used.

In the base case chalcopyrite is the only copper sulphide mineral and it is lost in copper flotation mainly as locked particles in those particles that are rich in sphalerite and pyrite (Figure 4).

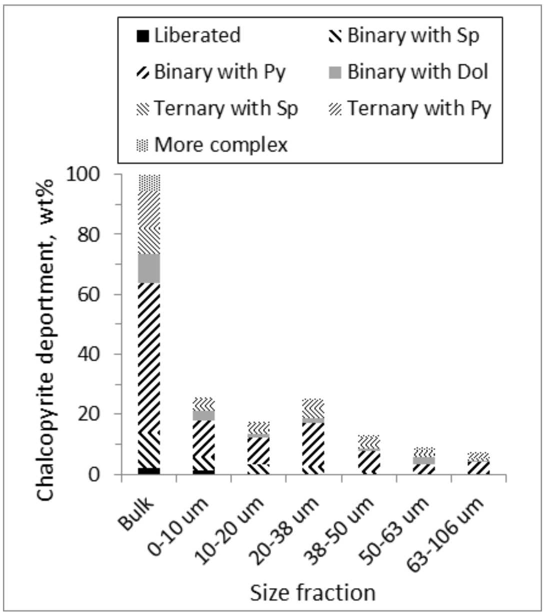


Figure 4: Chalcopyrite deportment in the copper flotation tailings, base case.

Fully liberated particles are practically fully recovered into the copper concentrate whereas the recovery decreases strongly as the chalcopyrite grade decreases in a composite particle (Figure 5).

Different problem cases were generated by introducing deviations into the simulation: for example change in the feed mineralogical properties (modal composition, texture), change in grinding circuit performance, change in mineral floatabilities. The circuit performance was found by running the simulation until the steady state was reached.

In the game the new metallurgical result was reported as key figures as shown in (Figure 3), i.e. elemental analysis for the key streams.

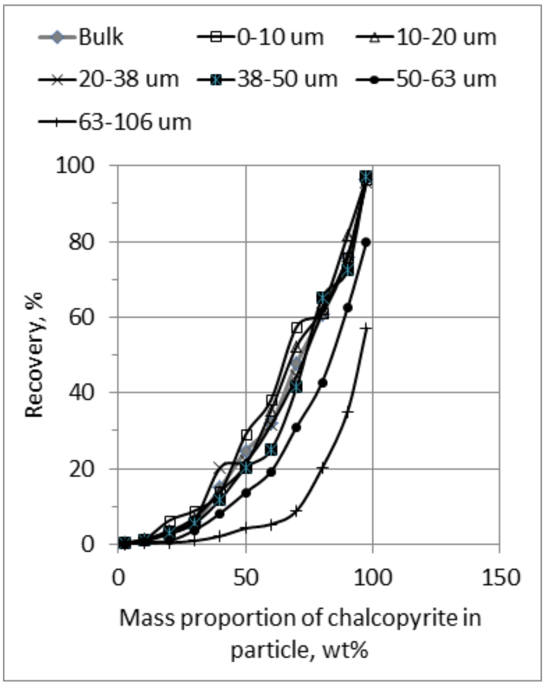


Figure 5: Recovery of chalcopyrite bearing particles into the copper concentrate by size.

For solving the performance problems a number of different process mineralogical methods are provided to the players. These include analysis methods for chemical composition of a sample, identifying minerals, modal analysis, chemical composition of minerals and mineral liberation (Table 1).

Each assay is assumed to take a certain time and having a certain price. In addition the game includes an error model for each assay, i.e. the analysis results do not directly report the information of the stream but add a random component that would follow a normal distribution if the assay was repeated.

In the game the players need to identify the problem with these available process mineralogical tools as fast as possible in terms of virtual time. If they succeed in this all the costs will be covered and they get a reward based on the time they spent compared to other players with the fastest getting the highest reward.

Table 1: Available tools for solving the process problems.

Item / method	Time (h)	Price (€)
Sampling, manual, incl. drying and measurement of %solids	4	25
Chemical analysis by X-ray fluorescence (XRF)	4	50
Chemical analysis (XRF) by size, incl. sizing	4	200
Particle size analysis by laser diffraction, P20, P50 and P80	1	50
Particle size analysis by sieving, 5 size fractions	24	100
Minerals by optical microscopy, own lab	2	Free
Minerals by XRD (X-ray diffraction	1	50
Minerals by XRD with Rietveld	2	100
Minerals by Automated mineralogy, incl sizing and resin mount	48	2500
Mineral chemistry by energy dispersive spectrometer (EDS)	8	200
Mineral chemistry by Electron microprobe	12	800
Liberation by Automated mineralogy, incl sizing and resin mount	48	2500

3.3. Solving the Problems

The solutions of sixteen problems from four different circuits have been tested with this game. When solving the problems the teams had good knowledge on different process mineralogical tools but their operating experience was practically non-existing. Problem solving scenarios and strategies weren't taught for the teams; thus they learned by doing, i.e. playing the game.

The problems can be divided into three main types, i.e. problems with 1) concentrate grade, 2) high impurities in concentrate (penalty), or 3) low recovery. Under each problem type there are several potential reasons. Totally seven different reason types have been included (Table 2).

Table 2: Problem/reason types tested.

Problem/reason types
Grades – Liberation-coarse grind – Liberation-texture – Modal change - new phase – Refractory (lower grade)
Grade-impurity – Entrainment – Floatability – Liberation-texture – Modal change - new phase – Refractory (impurity)
Recovery – Floatability – Liberation-coarse grind – Liberation-texture – Modal change - mass proportions – Modal change - new phase

4. CONCLUSIONS

During the course of the game the following common features could be identified in the strategies leading to successful solution of the problem:

- Recovery problems can be solved by studying first the tailing and after that the feed, if needed.
- An effective way of solving simple grade or grade-impurity problems is by studying the final concentrate first, then the feed and only after these, if needed, other streams (middlings).
- A quick particle size analysis on flotation feed should be used almost in any type of problems first. By that the hypotheses on changes resulting from the grinding stage can be efficiently excluded.

- Modal analysis proved out to be an effective way to test most of the hypotheses. The most effective method for modal analysis proved to be X-ray diffraction with Rietveld.
- Even liberation analysis is very valuable tool but it should only be used for testing the liberation-texture hypothesis. For modal analysis other methods, like Rietveld-XRD, should be used if mineral grades are higher than 1%.

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The observed student results and conclusions are fully in line with the developed diagnosis as presented in Figure 2.

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