

# **A way forward in process mineralogy – using automated mineralogy for modelling and simulating beneficiation processes**

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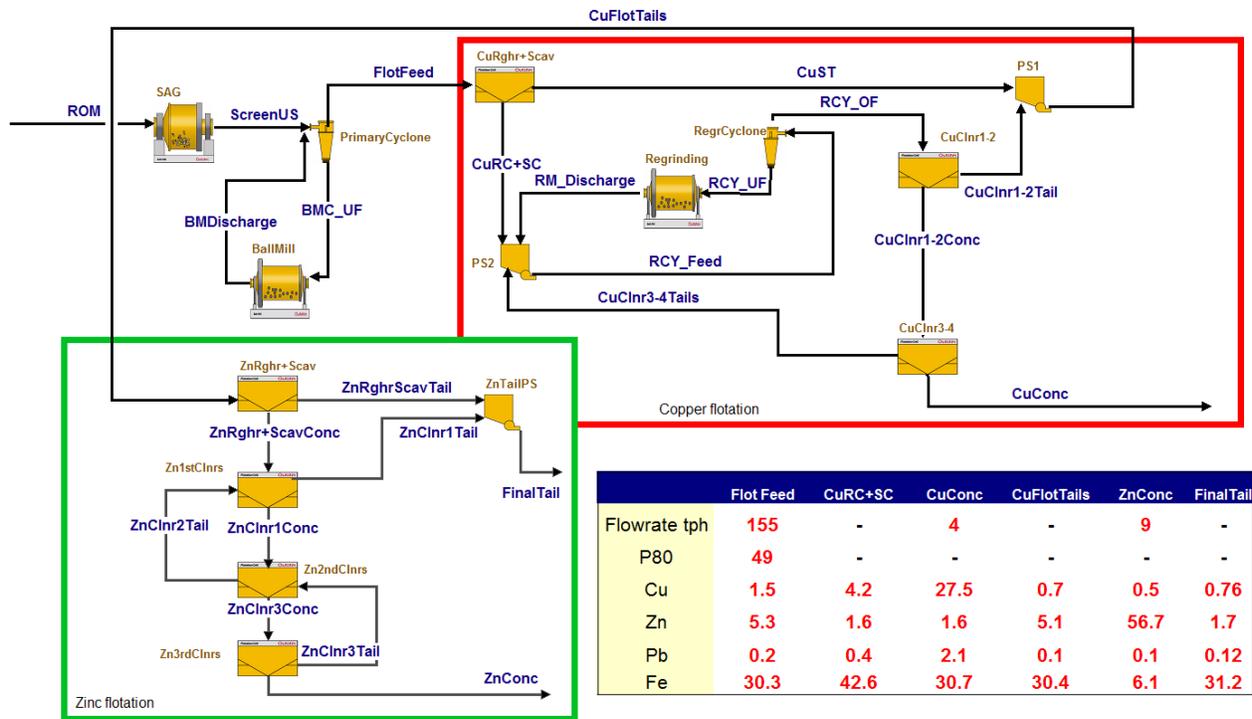
*Majority of the process mineralogical studies can be described as optimization problems where conditions for the best economic and most resource efficient processing are sought. For solving such a problem the raw process mineralogical data is not enough; optimal solution can be found only through modelling and simulation. Automated mineralogy provides accurate and detailed information on processed materials. Currently this data is only partly utilized since using of liberation information in modelling and simulation is very rare. This paper describes the steps needed for establishing such a simulations; from experimental work and liberation analyses via mass balancing, model development and model fitting to simulation of different scenarios. Challenges and limitations are discussed, case studies are presented and practical advices are given.*

## **Introduction**

Process mineralogy aims in solving practical problems related to minerals processing plants and for that it uses mineralogical tools (Lotter et al. 2011). In green field cases process mineralogy helps in defining the most suitable process for a given ore ensuring required product quality with good recovery (Lotter et al. 2011). In brownfield cases the questions deal with finding the reason for poor quality or for poor metallurgical performance (Lastra 2007; Gorain et al. 2000; Nel et al. 2005; Xiao & Laplante 2004; Xiao et al. 2009).

To teach how process mineralogy can be used in solving process problems in brownfield cases a serious game called Adventures of Process Mineralogist has been developed at Luleå University of Technology, Sweden (Lamberg & Rosenkranz 2014). The game is based on detailed process simulations built up by using mineralogical surveys of existing processes. Based on base case simulation teacher can create the problem cases by introducing a change in the plant feed or in the performance in the unit operations. An example of former is to decrease the mineral grain size causing poorer degree of liberation with given grind; and of latter is to make the efficiency curve flatter in hydrocyclone. Running the simulation to steady will generate complete picture of poorly performed circuit.

When students try to solve the problem they can take a sample anywhere from a process (see example in Figure 1) and analyze it with different process mineralogical analysis methods listed in Table 1. To make the game more realistic each analysis method has a price tag, delivery times and precision (Table 1). To increase their motivation students are set to compete against each other and the winner is the one who can find the right solution and give correct improvement suggestion in the shortest possible time (virtually) and with reasonable costs. The game has been used at four different universities within seven different higher education courses and the course evaluations verify that it is a powerful tool to teach process mineralogy.



**Figure 1.** Example of mineral processing circuit used in the serious game called *Adventures of Process Mineralogist*. Figures on right lower corner are analyses of daily production report.

The game has clearly shown three things. Firstly, without background information it is virtually impossible to diagnose the problem right. Therefore full mineralogical information is provided for all the process streams in the base case, i.e. when the process is working as designed. Secondly, without mass balancing it is very difficult to judge whether the differences the students find actually contribute to the magnitude of process problem. Thirdly, process mineralogy alone cannot say what would be the most beneficial way to solve the problem; it can only point out the possible ones. For example, in the problem described above, it would be relatively easy to diagnose that the reason for increased losses in the process are due to decrease in the degree of liberation of the mineral. But this does not answer whether this would be better to solve by grinding the material finer (e.g. by decreasing throughput) or it is better to accept the new operational point, since losses in throughput cannot be compensated with increase in the recovery. The seeking of the best economic or the most resource efficient solution is actually an

optimization problem. For solving such a problem the raw process mineralogical data is not enough. Optimal point(s) can be found only through modelling and simulation.

**Table 1. Methods available in the Adventures of Process Mineralogist.**

No	Item	Method	Time required, hours	Cost €*	Det. Limit	SD (RSD%)	Note
0	Sampling & %Solids	Manual	2	25	0.1	1	Includes drying and %Solids measurement
1	Chemical analysis	XRF	2	50	0.01	(2)	
2		XRF by size	10	300	0.01	(2)	Includes sizing
3	Particle size analysis	Laser particle size analyzer	1	30	0.1	(2)	P20, P50 and P80
4		Sizing (sieve fractions)	8	100	0.1	(1)	5 size fractions
5	Minerals	Optical microscopy	6	60	0.001	(10)	Your own lab
6		XRD	4	80	1	(10)	
7		XRD with Rietveld	6	100	1	(6)	
8		MLA	48	1000	0.01	(3)	Sizing + resin mount
9	Mineral chemistry	EDS	12	500	0.75	0.5	
10		EPMA	52	1500	0.01	0.1	
11	Liberation	MLA	48	2000	0.1	1	Sizing + resin mount

## Modelling and simulation of mineral processes

Traditionally in modelling and simulating of mineral processes only limited amount of mineralogical information is used (Table 2). In the modelling of comminution processes common practice is to fully ignore mineralogical properties (A, Table 2): only particle size distribution is forecasted and monitored. For building such a simulation grindability or other comminution characterization tests are used and these tests don't require any mineralogical information (Mwanga et al. 2014).

Concentration processes are mostly modelled separately from comminution circuits and common practice then is to investigate the process in fixed particle size distribution, i.e. on unsized basis (Table 2). It is not rare to find simulations which are based on chemical elements rather than minerals (B: Table 2). This approach has a risk to produce unrealistic results if the forecast is extended outside the experimental area. For example, building a floatability component model for chalcopyrite ore based on elements rather than minerals can give a forecast where concentrate grade is higher than 35 wt% Cu, which is impossible. The other reasons to build the simulation based on minerals rather than elements

are: the elements will have natural association from mineralogy and the bulk solids density (specific gravity) can be calculated reliably from mineral composition whereas if working with elemental grades normally the solids density of the stream is fixed even its composition can vary.

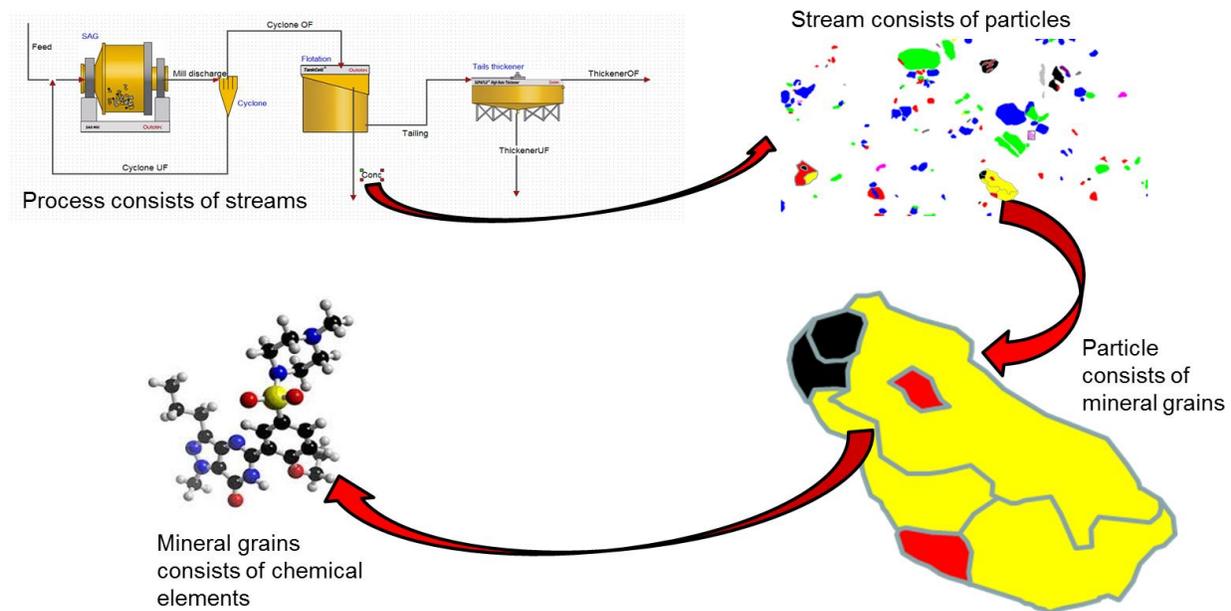
Modelling and simulation of mineral processes on mineral by size level gives possibility to study the effect of grinding fineness to metallurgical performance, and thus optimize the particle size distribution (2: Table 2). The model comes more robust and portable but as one of the key properties – mineral liberation – is missing, commonly each mineral needs to be divided mathematically to different components to match with the experimental results. For example, in flotation each mineral (by size class) is divided to fast, slow and non-floating to correspond to empirical results. Even though components have certain physical meaning, e.g. fast floating particles are the liberated ones in optimal particle size area, the liberation and component cannot be linked unambiguously (Welsby et al. 2010). For example, if model fitting gives as a result that 20% of certain mineral in certain particle size class is fast floating that does not mean that the degree of liberation is 20%. And this is also true other way round: if the degree of liberation of a mineral is, say 75%, it cannot be said that 75% of the mineral would be fast floating.

Mineral liberation data is very seldom used in modelling and simulating of mineral processes even it would be natural to describe the material with that dimension. Figure 2 illustrates the natural hierarchy of material in mineral processing. A mineral process consists of streams, which are made up of mineral particles (and liquid), particles consist of mineral grains and chemical elements are in the structure of minerals. The rarity of using mineral liberation information in models and simulations has been due to: 1) lack of easy and low cost system for mineral liberation analysis, 2) lack of process simulator capable to handle large data sets provided by automated mineralogy, 3) lack of unit process models which describe the behaviour of multiphase particles, 4) lack of robust tool for mass balancing mineral liberation data.

**Table 2.** Different levels used in modelling and simulation of mineral processes and their common field of usage.

<b>Composition / Particle size</b>	<b>Unsize</b> (particle size not considered)	<b>Sized</b> (particle size considered)
<b>No composition</b> (no compositional information on streams)	A: Basic engineering	B: Comminution
<b>Chemical composition</b> (chemical composition of streams given)	C: Separation processes, e.g. flotation based on floatability components	D: Separation processes, e.g. flotation using kinetic model
<b>Minerals</b> (modal composition of streams given)	1: Separation models, e.g. flotation based on floatability components	2: All mineral processes
<b>Liberation</b> (liberation distribution of streams given)	(not valid)	3: All particle based processes, models base on particle properties

Currently mineral liberation analyses are commonly available (Fandrich et al. 2007) and also simulators, which can take the mineral liberation information, exist (Roine 2009). However, the mineral processing models basing purely on physical properties and particle composition are still very rare. Also the mass balancing of liberation data is still not fully solved.

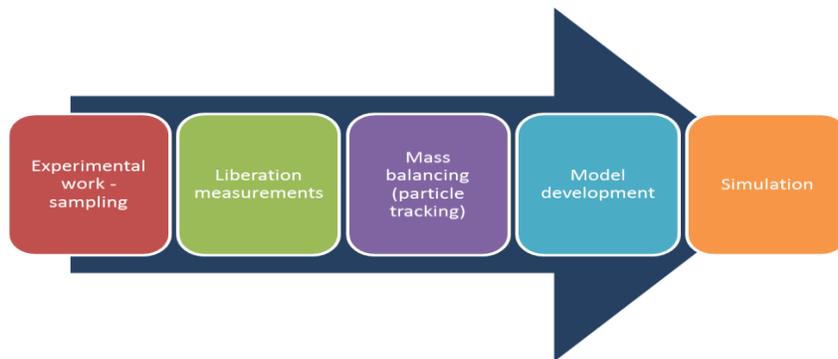


**Figure 2. Hierarchy of material in mineral processing circuits: process - streams – particles – mineral grains – chemical elements.**

## How to reach liberation level in modelling and simulation?

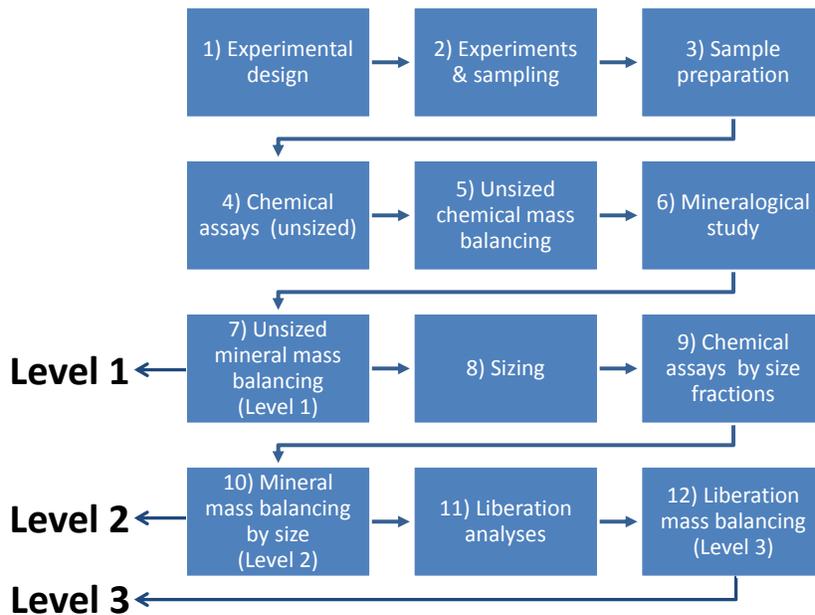
To reach mineral liberation level in the modelling and simulating the mineral processes requires model development which means experimental work (Figure 3). This needs to be designed in a way that all necessary parameters are considered and measured. Necessary streams need to be sampled followed by sample preparation, including sizing, and liberation analysis by size fractions. One should not forget duplicate samples and repeat assays for estimating the experimental error.

The developed models should describe the behaviour of particles in a unit process. Any model with more than one output streams needs finally to give distribution (coefficient) of each particle between the streams. Thus, models must predict recovery of each particle type in a unit process. For this information experimental work is needed. The raw liberation data gives grades of different kind of particles in streams and size fractions but it does not give recoveries. This information can be gained only by mass balancing (Hodouin & Everell 1980).



**Figure 3.** Stages needed to develop simulation basing on liberation data.

Mass balancing mineral liberation data is challenging for several reasons. Firstly, because of number of components to be mass balanced is large. In mineral or elemental mass balancing the number of components (i.e. minerals, chemical elements) is normally between 5 and 10 (e.g. Wills 1986). In liberation data the number of particles measured in each size fraction is often thousands. Secondly, the like hood of finding exactly identical particles, by composition and size, in each of the sampled streams is very low. Therefore particles must be first classified in a way that each stream has the same number of particles and their properties (composition and size) are identical in the whole circuit. Thirdly, the particle mass balance should be consistent with mineral and elemental mass balance on unsized (level 1 in Figure 4) and sized (level 2 in Figure 4) basis.



**Figure 4.** Mass balancing steps using the particle tracking technique (Lamberg & Vianna 2007). Level 1 refers to unsized mineral mass balance, Level 2 to size by mineral mass balance and Level 3 to liberation mass balance.

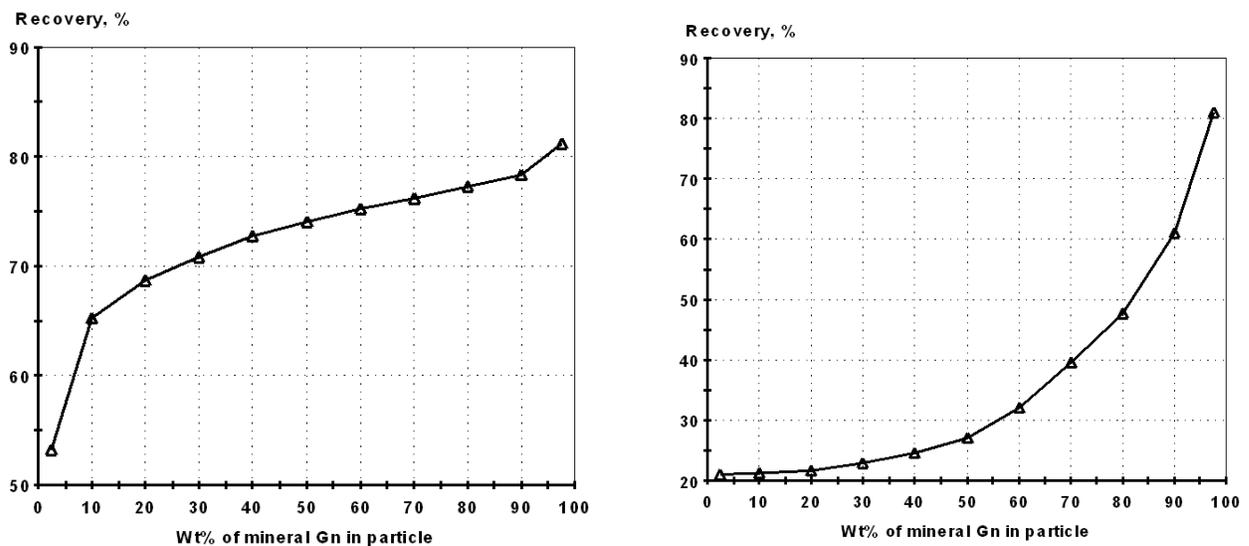
The mass balancing of liberation data was done first for binary systems (Savassi 2006; Vianna 2004). There exists two multiphase mass balancing technique: particle tracking developed by Lamberg and Vianna (2007) and technique developed by S. Gay (see Gay and Latti 2006 and JKMultibal<sup>1</sup>).

Once the mass balanced liberation data is available there are better possibilities to develop models which are based on physical properties of the mineral particles. One has access to mass balanced particle data where each particle class has properties like size, composition, density, magnetic volume etc. This enables to go to first principles and write equations based on forces or reaction equations particles experience in different unit operations or sub processes (King 2001; Youlton & Kinnaird 2013).

## Why to take the simulations into liberation level – way forward?

Taking mineral processing models and simulation into mineral liberation level requires more efforts than traditional approach using mineral or mineral by size level (Level 1 and Level 2 in Figure 4 and Table 2). What are the benefits this approach gives?

Lamberg & Vianna (2007) showed that galena-sphalerite and galena-quartz binaries have significantly different behaviour in flotation (Figure 5). Developing model to this level enables to forecast the metallurgical response of the material with different head grades and liberation distributions and thus giving possibilities for process optimization.



**Figure 5.** Recovery of galena bearing binary particles in Pb flotation, left galena-sphalerite binary particles, right galena-quartz binary particles.

<sup>1</sup> [www.jktech.com.au](http://www.jktech.com.au)

Youlton & Kinnaird (2013) developed a leaching model that forecasted the percentage uranium dissolution during acid leaching based on mineral liberation data. For a non-refractory ore the percentage of uranium dissolved was related to pH and the proportion of the U mineral grains exposed.

In recycling liberation approach has been used to model and simulate end-of-life products (Castro et al. 2005; van Schaik et al. 2004). The purpose of the model structure is to optimise material recovery and to minimise waste generation in recycling of end-of-life vehicles.

These examples demonstrate the benefits of using liberation data in creating particle based simulations.

The approach potentially:

- increases our understanding on behaviour of multiphase particles in different processes,
- opens up a way to first principles and fundamental models,
- enables to start to measure the properties of pure minerals in multiphase natural systems, e.g. to tabulate flotation rate of (fully liberated) sulphide minerals of certain size in certain conditions,
- makes our models more portable: models can take and predict the behaviour of ores with similar mineralogy but being different in terms of head grade and mineral liberation distribution.
- makes mineral processing models more reliable,
- enables to optimize full mineral processes including comminution, concentration and downstream processing,

Process mineralogy has developed during centuries from qualitative to quantitative. The next step which needs to be taken is to make it predictive.

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