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Towards the development of an integrated modelling framework underpinned by mineralogy

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ABSTRACT

The minerals industry is currently facing numerous multifaceted challenges spanning the techno-economic, environmental and social spheres. The adoption of sustainability thinking is a holistic approach to addressing these challenges and their relative interactions, rather than just focusing on individual units and processes. The ability to do so requires an integrated modelling framework underpinned by mineralogy, so that the effect of ore complexity and variability on one or more of these factors can be simultaneously evaluated and optimised. This study focuses on the steps towards the development of an integrated framework using a case study of a polymetallic sulfide ore flotation circuit. A unique ore specific element to mineral conversion recipe (EMC) was developed and validated, and after subsequent mass balancing across the circuit allowed the calculation of mineral grade and recovery throughout. By application of a set of mineral mass distribution functions across the circuit, and including a simple mineral-based model for the determination of tailings ARD potential, the integrated framework is used for scenario analysis. Two different scenarios are presented: the first considering the balance between improving copper concentrate product quality at the expense of increasing tailings ARD potential, and the second considering the effect of feed ore variability on tailings ARD potential. The framework provides a conceptual starting point for a new approach to traditional process mineralogy studies to start practising sustainability thinking.

1. Introduction

1.1. Background

The mining industry is faced with numerous multifaceted challenges within the realms of techno-economic, environmental and social issues (Deloitte, 2014; Bradshaw, 2014; World Economic Forum, 2015). Key challenges to the mining industry within the techno-economic space compromise rising operating costs alongside volatile metal markets where the balance between supply and demand is tenuous (Deloitte, 2014; Baxter, 2016). Technical difficulties in processing low grade, heterogeneous and mineralogically complex ores often necessitate the development of innovative technology (Prior et al., 2007; Mudd, 2009; Baum, 2013;Powell, 2013) In many cases, low-grade, complex ores require significant energy inputs for size reduction to liberate very fine-grained, disseminated valuable minerals (Pease et al., 2006). However, in the liberation and recovery processes of these valuable minerals, there may be unintended associated environmental consequences. Acid rock drainage (ARD) derived from mining activities is currently one of the most significant environmental problems facing the mining industry (Naidoo, 2017). Acid rock drainage is produced when sulfur-rich rocks are oxidised to form low pH waters with high sulfate contents and high concentrations of dissolved often toxic elements (Parbhakar-Fox et al., 2011). This results in the direct contamination of water resources in the vicinity of the mine and has far-reaching consequences to the surrounding communities, especially those residing in remote, arid areas (Ochieng et al., 2010; IFC, 2014).

The development of technology and skills that allow for the prevention and mitigation of ARD into perpetuity are therefore pressing concerns for the industry (Akcil and Koldas, 2006; Prior et al., 2007; Mudd, 2010; Parbhakar-Fox and Lottermoser, 2015). In the context of addressing these overarching multifaceted challenges, it requires the adoption of a holistic approach, allowing a series of unit operations or an entire circuit to be simultaneously optimised considering the inter-related techno-economic, environmental and social factors. The review paper by Edraki et al. (2014) on ‘designer mine tailings’ considered some of the more integrated approaches that have been proposed, for example:

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- The application of a two stage flotation process to the processing of fine coal discards allowing the recovery of a clean, saleable coal product, a small volume pyrite-rich product, and a high volume benign tailings product (Mbamba et al., 2012); or
- A computational approach in comparing the benefits of different circuit configurations in the flotation of high arsenic ores (Montenegro et al., 2013).

What these and other studies (e.g. Azapagic et al., 2006) have in common is their conceptual approach in addressing these interrelated sustainability challenges in the decision making process at both plant design stage and operation. However, most of these studies place limited focus on the role of mineralogical information and its acquisition and link to most downstream environmental impacts. An integrated modelling framework underpinned by minerology makes it possible to link ore variability to improved recoveries or grade and/or environmental impacts.

The Minerals to Metals Initiative at the University of Cape Town has a research project focused on developing an integrated modelling framework of the entire minerals value chain using mineralogy. Ultimately the framework should incorporate sustainability principles into the technical modelling framework for enhanced decision making (Charikinya et al., 2016). This paper presents the first step in the development of such a framework using a case study of a polymetallic sulfide ore. The study considers the effect of ore variability and operating conditions on metallurgical performance (grade, recovery) and on the potential for flotation tailings to generate acid rock drainage. The initial stages of the development focus solely on the interface between techno-economic and environmental aspects. Two scenarios are used to further illustrate its application, the first in terms of the balance of improving concentrate quality and its effect on final tailings acid rock drainage potential, and the second in terms of ore variability on final tailings acid rock drainage potential.

1.2. Guiding principles of the development of an integrated modelling framework

The guiding principle in developing the larger framework is to keep the approach *simple*, *cost effective* and *applicable*, so its strength lies in the ability to simultaneously evaluate several processes, rather than the detailed optimisation of any single specific unit operation. Since the framework is underpinned by mineralogy, the same applies to the mineralogical inputs - simple, cost effective, and applicable.

In the last two to three decades, the inclusion of mineralogical information into exploration, bench marking and optimising of mineral processing operations has been more widely practised (e.g.Schouwstra and Rule, 2016; Johnson, 2016). Mineral analytical techniques such as auto-SEM-EDS instruments (QEMSCAN, MLA, TIMA, Mineralogic) tend to be the ‘work horses’ for providing this quantitative mineralogical information on mineral grades, mineral grain size distribution, valuable mineral liberation and association characteristics (Wightman et al. 2016). Although the value of the information provided by these techniques is immense (Gu et al., 2014; Lotter et al., 2017), there are various practicalities associated with obtaining this information related to its high cost per sample, extensive sample preparation requirements, and on-site availability, suggesting it should not be considered the primary provider for mineralogical inputs to the initial framework development. Instead, a methodology that is simple, fast and inexpensive based on chemical assays which are more routinely available is considered – the element to mineral conversation method (EMC). A concerted effort is needed in establishing a unique ore specific recipe for the EMC, but once established (Lund et al., 2013), it may have extensive applications (note that each ore deposit requires its own EMC method and so the recipes are not directly transferable, although the principles behind the creation of the recipe are). The application of the EMC methodology here is not unique – since it has previously been applied in various other studies with similar requirements for simple, cost effective mineral grade calculations in geometallurgy (e.g. MacMillan et al. 2011; Lamberg et al., 2013). In most circumstances, the number of analyses in existing chemical assay datasets are several orders of magnitude larger than mineralogy datasets, thereby providing significant opportunity in converting the datasets to mineralogy.

The element to mineral conversion (EMC) methodology converts bulk elemental compositions into mineral grades by simultaneously solving a set of linear square equations (Lamberg et al., 1997; Paktunc, 1998; Whiten, 2007). The calculation requires both chemical (elemental) assays and known mineral compositions (mineral chemistry) for the ore in question. The calculation methods used are normally least squares, non-negative least squares, weighted least squares and weighted non-negative least squares. The calculations are specified by selecting subgroups of minerals and their associated elemental information into a series of rounds, where the residual is minimised. The mineral grades are calculated sequentially, and subsequent rounds continue until all the minerals in the list have been allocated. This gives better control in cases where the least squares method does not give a solution and a non– negative equation has to be used. The sum of the calculated mineral grades cannot exceed 100% or be negative. If there are more elements than minerals, the case is over-determined, and there is more than one solution. If the number of minerals is higher than elements, the case is under-determined and there is no unique solution (Paktunc, 1998;Whiten, 2007). The method only gives bulk mineralogy and does not give information on grain size, association and liberation.

In following the guiding principles of keeping the framework simple, cost effective and applicable, is the consideration of the types of models which are incorporated. Therefore the more mechanistic – empirical models that find application in the dedicated optimisation of specific unit operations, (e.g. floatability component model approach; Méndez et al., 2009; Jamett et al., 2012) are not incorporated. These models require extensive plant data for calibration, which was beyond the scope of this initial study. Since the purpose of this study was to demonstrate the conceptual approach and potential application of the sustainability modelling framework, the mineral distribution function (also sometimes known as a mineral splitter function) was considered to be adequate. The mass distribution function, calculates mineral separation based on given mineral recoveries. These recoveries are calculated from a plant mass balance and are assumed to be constant during the evaluation of different scenarios. This modelling approach has been shown to be a valid initial first step in identifying scenarios for further detailed investigation. However further investigation of scenarios would require flotation models based on experimentation (Montenegro et al., 2013).

1.3. Methodologies for acid rock drainage (ARD) characterisation

Acid rock drainage (ARD) characterisation and prediction is important, as it allows for the advanced planning for prevention and mitigation of ARD. The practice of ARD characterisation is broadly divided into methodologies that simply determine whether the material has the potential to generate ARD, and if so determines the “quality” of the ARD (pH, TDS, concentration and type of associated deleterious elements etc.); and tests (both experimental and computational) that provide more information on the trajectory of ARD generation over time (Plumlee et al., 1999; GARD, 2009; Dold, 2016). It is acknowledged that the field of ARD characterisation and prediction is a complex space where numerous competing factors need to be considered for the more fundamental and detailed modelling approaches, e.g. mineral type, mineral texture, particle size, porosity, fluid flow, microbiology, associated secondary precipitation and dissolution reactions, and background element concentrations (Lottermoser, 2010; Parbhakar-Fox and Lottermoser, 2015). These factors are however, beyond the scope of the integrated framework. In keeping with the overarching objectives the initial framework development is focused on the application of