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Integration of mineralogical attributes in evaluating sustainability indicators of a magnetic separator

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ABSTRACT

Early integration of sustainability decisions and mineralogical attributes into the design of minerals processing units offers potential for reducing environmental impacts at mining and processing sites. The objective of this study is to demonstrate how the integration of sustainability indicators and mineralogical attributes could be achieved in developing an integrated modelling framework of a magnetic separator. A magnetic separator unit model based on existing literature was developed to include process stream mineralogical data and to output sustainability indicators. The overall sustainability of processing three ore types (low, medium and high grade iron ore) was evaluated using the developed model. Novel measures for evaluating magnetic separation (Grade Recovery Deviation Index (GRDI)) and energy efficiency (Rotational Energy Transfer Efficiency (RETE)) that incorporate the use of ore characteristics were developed in this study. These measures were used to calculate the separation and energy efficiency sustainability indicator ratings. In total eleven magnetic separator sustainability indicators were identified. Each indicator was assigned a weighting value out of 10 based on its importance. Of the 11 sustainability indicators identified; safety, reliability, Carbon dioxide (CO_2) emissions, water use, noise and job creation ratings did not vary with changing mineralogical attributes of the feed ore. GRDI, RETE, electricity cost, particle emissions and waste generation ratings were observed to be dependent on the ore characteristics and therefore their values varied with different feed ore grades. The Analytic Hierarchy Process (AHP) and Weighted Sum Method (WSM) methods were applied to the sustainability indicator ratings and weightings to evaluate an overall sustainability cardinal score of processing a particular ore feed. Results of this study demonstrate the dependence of overall process sustainability indicators on feed ore mineralogical attributes. The results also provide an indication of the effect of ore variability (typical within a single deposit) on sustainability indicators.

1. Introduction

Minerals and metals are essential for modern life and their reliable and responsible supply is critical to maintain and develop a sustainable world. However, their extraction and beneficiation has significant negative environmental impacts such as the contamination of water, air and land resources with toxic by-products from their processing (Durucan et al., 2006; Edraki et al., 2014; Rosenkranz and Lamberg, 2014; Schoenberger, 2016). Currently, there is growing pressure for the mining industry to improve on its environmental performance by adopting sustainability principles in minerals and metals production (Azapagic, 2004; Batterham, 2014; Pimentel et al., 2016). This improved sustainability can be achieved by selecting and improving beneficiation methods and processes to produce minerals and metals with improved technical, economic benefits, but also with reduced environmental and social impacts. Thus, attempts to pursue sustainability in the minerals sector have largely focused on developing new technologies for both existing and alternative metal production processes that reduce the environmental impacts (Kazadi Mbamba et al., 2012; Kingman et al., 2004; Norgate et al., 2007; Rule et al., 2009).

The beneficiation and upgrading of minerals and metals is determined by their inherent mineralogical properties: bulk mineralogy, mineral chemistry and texture (liberation and association), as well as the variability of these attributes (Ghorbani et al., 2013; Hunt et al., 2011; Tungpalan et al., 2015). Most

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environmental impacts observed downstream of the beneficiation process can be traced back to the mineralogical properties of the feed ore (Dold and Fontboté, 2002; Edraki et al., 2014; Parbhakar-Fox et al., 2011). Integration of sustainability indicators into process unit models that input mineralogical data offers greater potential for reducing environmental and social impacts at mining and processing sites (Norgate et al., 2007; Tuazon et al., 2012).

Determining the overall sustainability of a unit process requires the assessment of the impacts of all relevant aspects of the unit process operation on technical, economic, environmental and social sustainability criteria for energy supply systems by decision makers. Multi-Criteria Decision Analysis (MCDA) is a decision making approach that can be used to aid in sustainability evaluation. Traditional single criterion approach to decision making in sustainability evaluation of process operations is normally aimed at identifying the most efficient process options that minimise production costs. The advantage of MCDA over the traditional approach is the ability of MCDA to employ a multi-criteria approach to obtain an integrated decision making result (Wang et al., 2009). A complete MCDA comprises of four sections; criteria selection, criteria weighting, evaluation using ranking methods and ordering or aggregating the results (Omann, 2004; Wang et al., 2009). The selection of criteria can be complex for large plant designs in which there are numerous factors to consider. The weighting of criteria can be performed using various methods, such as the Weighted Sum Method (WSM), Compromise programming (CP), Multi-attribute utility theory (MAUT), Weighted product method (WPM) and Analytic Hierarchy Process (AHP) (Pohekar and Ramachandran, 2004; Wang et al., 2009).

Integrating unit models that utilise mineralogical data with MCDA methods offers an opportunity for developing better decision making techniques that incorporate sustainability indicators. These integrated modelling frameworks will offer a tool for making decisions based on technical, economic, environmental and social sustainability aspects. The objective of this study is to demonstrate how integration of sustainability indicators and mineralogical attributes could be achieved in developing an integrated modelling framework of a magnetic separator. The study aims to develop a means of quantifying the effect of ore variability on separation and energy efficiency sustainability indicators by defining new methods of calculating these indicators. The study further aims to develop metrics for quantifying an overall sustainability rating which is used to determine the degree to which a process scenario balances the technical, economic, environmental and social sustainability aspects. Within the context of this study sustainability relates to magnetic separator process operations that balance the technical, social, economic and environmental aspects.

2. Methodology

2.1. Ore samples

Magnetic separation tests were carried out using a Mörtsell laboratory magnetic separator with 5 kg feed samples, 270 mm roller diameter and 127 mm roller length (Lund et al., 2015). Magnetic separation tests were conducted on high, medium and low grade magnetite bearing iron ores typical of the Kiruna type deposits in the Norrbotten province in northern Sweden. Representative feed samples from each ore grade were thereafter split and sized for further chemical and mineralogical analyses. Polished blocks of −45, +45/−90, +90/−180, +180/−500, +500/−1400 and +1400 μm fractions were prepared and analysed on an FEI FEG QEMSCAN 650F to determine the bulk mineralogy and mineral associations using both the Field Image analysis and Particle Mineralogical Analysis routines. The QEMSCAN measured bulk mineralogical data were validated with XRD, XRF and wet chemistry (for Fe^{2+}). Following the initial post analysis data processing, the particle data was exported from the QEMSCAN iDiscover software into Excel© and read into SciLab© for further modelling.

2.2. Magnetic separator modelling

Magnetic separation is used to separate materials based on their magnetic susceptibility. Magnetic separation operations can be categorized into high intensity (up to 20,000 gauss) and low intensity (1000–3000 gauss) techniques (Birss et al., 1979). The Hopstock model has been widely used in modelling magnetic separators (Hopstock, 1975; King, 2012). The Hopstock model relies on knowledge of the radial force experienced by a particle at the surface of the drum which can be determined via the product of the magnetic force density and the magnetic volume of the particle (King, 2012). Particle trajectory is largely controlled by magnetic, centrifugal, and gravitational force. Cakir et al. (1977) used Hopstock's model of magnetic fields to develop a mathematical model for particle trajectories. The Cakir model calculates the angular velocity of the particles along the magnetic separator roller which allows for more accurate determination of particle trajectory both on and off the roller surface (Cakir et al., 1977).

The model for simulating magnetic separation used in this study consists of combining elements of the Hopstock and Cakir models (Cakir et al., 1977; Hopstock, 1975). The developed model calculates the trajectory of a single particle based on its and magnetic separator properties such as field strength (Robertson and Platts, 2015). QEMSCAN data files for each size fraction were used directly to represent the feed ore particles in the magnetic separator simulations. In the QEMSCAN data, each particle within a size fraction was attributed with a particle or grain area, particle or grain perimeter and modal composition data. The composition consisted of a list of minerals, along with the mineral percent of particle area and the mineral percent of the particle circumference.

2.3. Developing measures of process efficiency incorporating mineralogical data

Measures for evaluating magnetic separation and energy efficiency that incorporate the use of ore characteristics as represented by mineralogical data and magnetic properties of particles were developed in this study. A Grade Recovery Deviation Index (GRDI) for quantifying the separation efficiency, and the Rotational Energy Transfer Efficiency, as a measure of energy efficiency were developed and calculated for each feed ore considered in this study.

2.4. Sustainability criteria ratings

The AHP and WSM methods were used for measuring the overall sustainability of processing magnetite ores of different grades. For AHP Twelve $[n \times n]$ pair wise comparison matrices (where n is the number of criteria being compared), one for each of the criteria ratings and a twelfth for the overall weightings were constructed based on the output of the magnetic separation model. The rating matrix entries were calculated by dividing the corresponding ratings for each entry and likewise, the weighting matrix entries were calculated by dividing the corresponding weightings for each entry. Principal eigenvectors for each of these rating and weighting matrices were calculated as shown in Eq. (1). The components of the eigenvector for the rating matrices were then each multiplied by the corresponding components of the weighting matrix eigenvector. These products were summed to get a relative cardinal score for each of the three grades of ore (Eq. (2)).

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