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Value driven methodology to assess risk and operating robustness for grade engineering strategies by means of stochastic optimisation

C. Carrasco [a,b,*], L. Keeney [a,b], M. Scott [a], T.J. Napier-Munn [b]

[a] Co-operative Research Centre for Optimising Resource Extraction (CRCORE), Brisbane, Australia
[b] Julius Kruttschnitt Mineral Research Centre (JKMRC), The University of Queensland, Brisbane, Australia

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A B S T R A C T

Grade Engineering® spans a range of operational techniques that exploits intrinsic grade variability to remove low grade uneconomic material prior to energy intensive and inefficient grinding.

Grade Engineering provides an additional level of operational flexibility while also incurring complexity that needs to be managed for an effective operational deployment. An integrated value driven methodology has been developed to manage this complexity by means of stochastic optimisation. This allows the optimum Grade Engineering processing "recipe" to be determined that maximises value per unit of time that can be drawn from a production volume under a set of user defined constraints. The introduction of uncertainty in the stochastic optimisation problem enables the assessment of the risk and operating robustness, both essential in robust decision-making processes.

The case study discussed in the paper comprises a large open cut copper porphyry deposit for which two Grade Engineering strategies are assessed: differential blasting for grade, and preferential grade by size response. These size-based coarse separation levers are subsequently exploited through a Grade Engineering circuit. This comprises a set of screens and crushers, with a configuration and operating settings defined by the Grade Engineering recipe.

The methodology developed demonstrated that size-based Grade engineering is a robust operating option that can effectively deliver significant improvements in unit metal productivity.

1. Introduction

1.1. Mining moving towards a manufacturing industry through flexibility

The global mining industry is currently focused on improving unit metal productivity and energy efficiency in order to fulfil increasing demand for natural resources. These are currently being impacted by increases in processing costs and the trend of reduced ore body grade (Napier-Munn, 2015; Bearman, 2012; Prior et al., 2012; Topp et al., 2008).

Novel operating strategies such as flexible circuits (Powell et al., 2014; Foggiatto et al., 2014; Powell and Bye, 2009) and Grade Engineering (Walters, 2016; Carrasco et al., 2016a, 2016b, 2016c) seek to provide an additional level of operating flexibility to exploit inherent ore body variability, enabling resource as well as process optimisation. Nevertheless, this flexibility presents significant challenges to the current standard operating philosophy which is mainly focused on maximising material quantity, rather than quality.

Industries with a significant level of flexibility such as manufacturing, chemical and oil and gas have coped with the associated complexity through the development of decision support and execution systems (Engell and Harjunkoski, 2012; Frost and Sullivan, 2010; Scholten, 2007; ANSI/ISA-95, 2005). This has been done in conjunction with new approaches to data integration to understand the impact of flexible operation decisions across the entire system value chain (Engell and Harjunkoski, 2012; Harjunkoski et al., 2009; Wassick, 2009; Smith, 2005; Sakizlis et al., 2004). A clear example of this flexibility successfully implemented in the refining process of the oil and gas industry is discussed in this paper. This process can be divided into three areas: crude operation, production and blending.

A variety of crude oil can be fed to the production plant, characterised by its flexibility to accommodate a range of flow rates, compositions and physical/chemical properties (density, flash point, etc.) to produce a variety of saleable products. These are subsequently blended to meet a dynamic product demand. However,

* Corresponding author at: Co-operative Research Centre for Optimising Resource Extraction (CRCORE), Brisbane, Australia.
E-mail address: c.carrasco@crcore.org.au (C. Carrasco).

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variability in feed characteristics are often difficult to quantify and are therefore uncertain (e.g. inconsistencies in the feed stock, coupled with variations in the performance of upstream processes) (Mesfin and Shuhaimi, 2010; Cao et al., 2009). Hence the problem in this flexible production environment is to make the process economically optimal, but still feasible under uncertain feed conditions. As these decisions are made in close to real time, it is essential to take into account the possible nonlinearities in process operations through detailed process models. This is in opposition to simple linear representations of production processes that are generally adequate for strategic/long term based decisions (Newman et al., 2010; Wassick, 2009).

This has been addressed through process optimisation under uncertainty, also referred to as stochastic optimisation (Navia et al., 2014; Birge and Louveaux, 2010; Sahinidis, 2004; Wendt et al., 2002). This aims to deliver robust processing decisions which have been extensively applied across process design, operation and control (Gabrel et al., 2014; Sahinidis, 2004) in the aforementioned industries, and to a lesser extent, in mining. A novel decision support tool referred to as Ore Logic® has been developed to support Grade Engineering deployment at an open cut copper porphyry deposit. Two GE size based separation techniques are extensively analysed; preferential grade by size deportment (Carrasco et al., 2016a, 2014; Carrasco, 2013) and differential blasting for grade (Carrasco et al., 2016c).

The former refers to a natural based rock property whereby a significant metal proportion preferentially deports into specific size fractions after breakage. Differential blasting aims to change blast product fragmentation to "induce" grade by size deportment through the exploitation of deposit spatial grade heterogeneity characteristic. This relates the presence of spatial high grade and low grade discrete clusters within a certain production volume originally assigned to a single destination (e.g. waste, leach, and mill) based on its average grade. In differential blasting for grade, high levels of energy are applied to high grade pockets and low energy is imported to low grade zones, allowing high and low grade cluster fragmented rock to be separated based on their different particle size distributions, via screening.

These size based separation responses are exploited through a Grade Engineering circuit, consisting of a set of screens and a crusher, which were modelled with the widely accepted JKMRC performance models (Napier-Munn et al., 1996) to better describe the nonlinear interaction between rock based properties and equipment performance.

This tool enables the Grade Engineering (GE) strategy to be assessed not merely for value, but for robustness and flexibility. Ore Logic® comprises 5 modules as shown in Fig. 1. The first module is associated with uncertainty modelling, where information from an industrial GE screening trial has been employed. The aim is to estimate the probability density distributions of the GE inputs later used in the stochastic optimisation module (Carrasco et al., 2016d). The second module takes into account variations in comminution and flotation performance due to changes in standard mill feed particle size distributions (Carrasco et al., 2016c). The third module predicts changes in grade by size responses due to breakage, using a statistically robust coarse liberation model (Carrasco et al., 2016b). The fourth module employs the aforementioned inputs to perform a chance constraint stochastic optimisation (Mesfin and Shuhaimi, 2010; Li et al., 2008; Sahinidis, 2004) through sample average approximation (Shapiro, 2013; Pagnoncelli et al., 2009; Shapiro and Wardi, 1996) and a customised genetic algorithm. This determines the optimum material processing destination, a GE processing recipe consisting of the optimum processing path and GE operating settings (screen apertures and crusher closed side setting). The final Ore Logic component, data analysis, performs comparative statistical tests (e.g. *t*-test) and a robustness analysis analysing the interaction between the objective function and the feasible region defined by the constraints.

2. Optimisation under uncertainty (stochastic optimisation)

Optimisation under uncertainty or stochastic optimisation refers to a collection of methods for minimising or maximising an objective function when uncertainty is present. Each of the uncertain data inputs are described in terms of the probability distribution (e.g. Gaussian, log-normal) while its correlation with other variables is also characterised. These uncertain variables are propagated through the process to the output variables. The aim is to integrate the available stochastic information in the optimisation problem.

Stochastic problems can be essentially divided into two different categories, those which involve a sequence of decisions over several time periods (multistage problems), or those involving a single time period (single stage).

The multistage approaches seek to find an optimal sequence of decisions over a certain period of time. This approach has been extensively used in long term strategic scheduling and planning problems. In mining this approach has received great attention in the last decade (Dimitrakopoulos and Godoy, 2014; Montiel and Dimitrakopoulos, 2013; Godoy, 2003; Dimitrakopoulos et al., 2002). The uncertainty is modelled through geological conditional simulation and therefore accounts for ore body knowledge uncertainty. However, this is beyond the scope of this work.

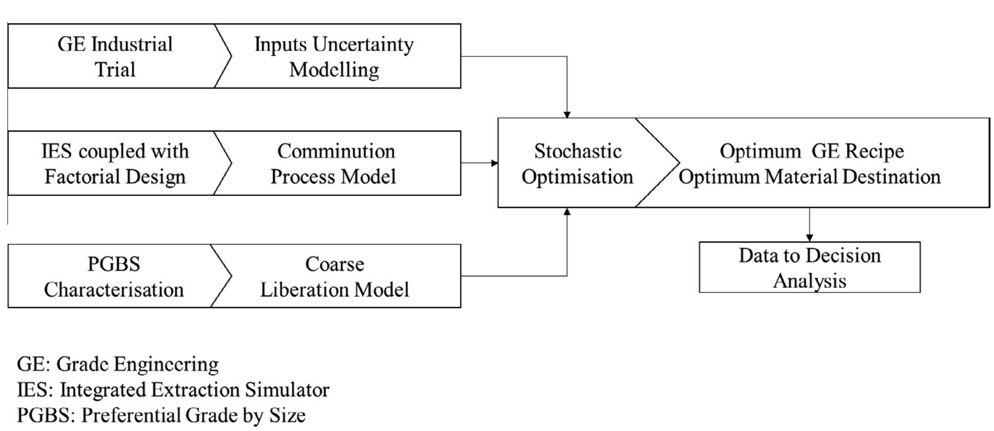

Fig. 1. Ore Logic® structure.