Minerals Engineering 145 (2020) 106072

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Towards integrated geometallurgical approach: Critical review of current practices and future trends

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ARTICLE INFO

Keywords:
Resource efficient
Mineral processing
Primary resources
Geometallurgy
Modelling and simulation
Mine's production chain

ABSTRACT

Geometallurgy has become an important tool for mitigating production risks and improving economic performance in the modern mining industry. Multiple definitions and visions of geometallurgy have been proposed during the last decades. Most of them define geometallurgy as a bridge between geology and mineral processing. Such a definition is rather confusing since process mineralogy claims to be such "bridge" too. Therefore, the main objective of the present paper is to provide a broad image of geometallurgy covering planning, executing and evaluation of geometallurgical programs. Such a vision of geometallurgy was developed within a research project PREP, which was aimed at "resource effective mineral processing". PREP is a holistic geometallurgical approach independent of deposit type. The approach differentiates geometallurgical programs based on the complexity of the problem and the desirable outcome. Particular attention was paid to the planning of the geometallurgical programs, data management, and new tools development. The practical usage of the approach was tested with three case studies: iron-apatite ore, VMS, and Cu porphyry deposits. Some examples of applying geometallurgy for the iron-apatite ore are shown in this paper. The result, the guidelines on planning, executing and evaluating a geometallurgical program, are given in this paper.

1. Introduction

Increasing demand for high quality raw materials have forced the mining industry to focus more on deposits which would not be considered as economic previously due to geological and mineralogical complexity and heterogeneity, low grades, higher consumables costs (energy, water, and chemicals), fine-grained ore texture, deleterious elements, and the variable response of the process (Dominy and Connor, 2016; Dunham and Vann, 2007; Mudd and Jowitt, 2016; Powell, 2013; Walters, 2011). Dealing with such deposits created demand for more advanced production systems (e.g., ISA mill (Pease et al., 2005), ore tracking systems (Jansen et al., 2009), process monitoring (Remes, 2012)). As a result, more professions started to be involved with mine production (e.g., automation engineers, maintenance engineers, environmental engineers, and data analysts). It became more difficult to assign key performance indicators (KPI) which would lead to an overall improved performance of the production and would not create conflicts between different parts of the mining value chain. For example, the average metal grade in a run-of-mine (ROM) ore which is a common KPI for a mine, does not always correspond to high metal recovery which is a common KPI for a concentrator. The difference in objectives is obvious in the case of many porphyry copper deposits. Copper in those deposits is present as oxide and sulfide minerals, while the concentrator can be limited to processing only one type of ore, either oxides or sulfides. Therefore, high grade Cu oxide run-of-mine ore will correspond to poor recovery in a circuit designed for copper sulfides.

Contradiction and poor setting of KPI's are good grounds for using geometallurgy. Therefore, geometallurgy is a tool for reducing production risks by bridging different parts of the mining production cycle through improved communication, new technologies, and suggested solutions acceptable for all stakeholders.

Geometallurgy emerged as a result of cooperation between geology and mineral processing. This is not sufficient anymore, because neither of these possesses the whole knowledge needed for the optimization of the entire value chain.

The aim of this paper therefore is to present a novel integrated geometallurgical approach developed at Luleå University of Technology (LTU) under the project name PREP (primary resource efficiency for enhanced prediction). The current definition of geometallurgy was

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https://doi.org/10.1016/j.mineng.2019.106072
Received 3 May 2019; Received in revised form 10 September 2019; Accepted 6 October 2019

Table 1
Steps in the geometallurgical program (numbers in table show preferential order of execution of a geometallurgical program).

#	Steps of a geometallurgical program	References										
		R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11
1	**Design/planning**		1					2	1			
2	**Team allocation**		2									
3	**Domain definition**	1a, 4		1	1						1	3, 2
4	**Sample Selection**	2	3	2	2	1	1	3d	2	1		
5	**Mineralogical/chemical/physical characterization**						2	1			2	
6	**Metallurgical test work**	3	4	3, 4c	3	2	3	4	3	2, 3e, 4f	3	1, 3. 1c
7	**Data management**		5									2h
8	**Process modelling**	5	6	5	4			5		5	4	3.3
9	**Plant simulation**	6b, 7										
10	**Geometallurgical block model estimation**			6	5	3	4	6	4		5	4i, 5
11	**Process model calibration with operations**	8										
12	**Mining and mineral processing optimization**		7g	7	6			7	5			
13	**Economic modelling**							8	6			
14	**Risk assessment**							9				
15	**Environmental modelling**							9				
16	**Subsidence prediction**							10				
17	**Change management and work culture**								7			
Iterative when specified			Yes	Yes	Yes			Yes				Yes

References: R1 (Lamberg, 2011); R2 (McKay et al., 2016); R3 (Turner-Saad, 2010; SGS, 2013a, 2013b); R4 (Bridge et al., 2014); R5 (Kittler et al., 2011); R6 (Beniscelli, 2011); R7 (Sola and Harbort, 2012); R8 (Vann et al., 2011); R9 (Leichliter et al., 2012); R10 (Baumgartner et al., 2011); R11 (Keeney and Walters, 2011).
Comments: a - Collecting geological data; b – Process modelling for simulation; c – Variability test work as opposite to metallurgical test work; d – sampling for test work; e - Medium (bench) scale test work; f - Large scale test work; g – only for tactical geometallurgy as opposite to strategic; h – data analysis; i – geometallurgical domaining.

obtained through a literature review. Given the discoveries made during the PREP project and current trends in the industry, we suggest new directions for the development and applications of geometallurgy.

The practical implementation of the results of the PREP project can be found in a number of journal publications (Lishchuk et al., 2018; Lishchuk et al., 2019a, 2019b), conference papers (Koch et al., 2015; Koch and Rosenkranz, 2017; Lishchuk et al., 2016a, 2016b, 2015b), licentiate and doctoral theses (Koch, 2017; Lishchuk, 2016, 2019), and master theses (Bilal, 2017; Cárdenas, 2017; Singh, 2017; Tiu, 2017) published at LTU between 2014 and 2019. More publications are scheduled in 2019–2020 to disseminate the results of the PREP approach developed within the PREP project.

2. Definition of geometallurgy

The key parts of the mining value chain are geology, mining, mineral processing, process metallurgy, waste management. Traditionally, the mining industry treats exploration and mining geology, mining and processing as separate parts of the value chain with little connection between them. Bridging mining and processing (mainly mineral processing) is often called mine-to-mill. Establishing a link between geology and downstream processes is referred to as geometallurgy. Some overlaps and confusion occur between mine-to-mill and geometallurgy. In general, geometallurgy tends to neglect the impact of the mining method on the process, while mine-to-mill tends to avoid downstream processes after the comminution stage. However, the trend is to see them as a part of the same approach.

Another aim of geometallurgy is to reduce production risks and improve production planning for better managerial decisions. This is achieved by quantifying the variability of mine production properties/responses with geometallurgical models. Work related to the creation of such models is called a geometallurgical program. Currently, four types of processes are considered in geometallurgy:

- Mining (i.e., blasting as a part of comminution);
- Mineral processing (i.e., crushing, grinding, flotation, magnetic separation, dewatering etc);
- Process metallurgy (i.e., pelletizing and sintering (Suthers et al., 2016)); and
- Environmental (i.e., acid mine drainage (Dold, 2016), mine waste (Mudd and Jowitt, 2016)).

The ore processing properties must be easily and accurately measured at a low cost. Tests, which satisfy those conditions, are called geometallurgical tests (opposite to traditional mineral processing tests) (Koch et al., 2015; Mwanga et al., 2017).

Geometallurgical models are built by identifying key geological/physical/mineralogical/chemical properties of the ore samples ("input properties") and linking them to the process properties ("output properties"). Those input properties are typically treated as multivariate data and are determined on several test samples. The ultimate product of geometallurgy is the distribution of metallurgical parameters through an orebody (block model, or the mine plan) reached by applying accepted geostatistical techniques (Lamberg, 2011).

Since the mining industry is rather conservative, implementation of geometallurgy is not straight forward. For instance, change management (Vann et al., 2011) could be used for implementing geometallurgy at site.

Multiple definitions of geometallurgy have been proposed during the last decades (Appendix A). Some of them are more specific to the treated commodity, others to the process. The 5 W + H (Ikeda et al., 1998; Jia et al., 2015) analysis was used to analyse these definitions (Appendix A) 5 W + H stands for six questions, which have to be answered regarding the studied topic:

1. Who? – who are the main actors involved in geometallurgy;
2. What? – what is the definition of geometallurgy;
3. Where? – where was the definition applied in practice;
4. When? – at which stages of the mining project should geometallurgy be applied;
5. Why? – why is this definition relevant; and
6. How? – how to implement geometallurgy and which steps must be taken.

Scholars mostly agree on the steps and their order within geometallurgical program by emphasizing (word removed) sample selection, test work and modelling (Table 1). However, only a few pointed out the importance of preliminary planning, economic and environmental