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Designing gold extraction processes: Performance study of a case-based reasoning system

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A B S T R A C T

This paper presents a method for externalising and formalising knowledge involving the selection of hydrometallurgical process flowsheets for gold extraction from ores. A case-based reasoning (CBR) system was built using an open source software myCBR 3.0. The aim of the systems is to recommend flowsheet alternatives for processing a potential gold ore deposit. Nine attributes: *Ore type*, *Gold ore grade*, *Gold distribution*, *Gold grain size*, *Sulfide present*, *Arsenic sulfide*, *Copper sulfide*, *Iron sulfide* and *Clay present* were modelled and several literature sources of actual gold mines and processes were used for acquiring cases for the system. After preliminary testing, functional evaluation of the built CBR system was carried out by using five real mining projects as test cases. Additionally, human experts in the field of gold hydrometallurgy were interviewed to demonstrate the benefits of the CBR system as it holds no human biases towards any processing techniques. It was found that the suggestions of the CBR system provided useful information and direction for further process design and performed well compared to the interviewed human experts, thus confirming that the system is of practical relevance to the process engineer designing an industrial gold processing plant. The current model was found to be a functioning basis for further development through additional attributes, adjusted attribute weighting and increased number of cases.

1. Introduction

The governing method for gold ore processing has been cyanide leaching since the late 19th century (Marsden and House, 2006). After decades of active development of the process for various types of ores and concentrates, there are several different hydrometallurgical flowsheets for cyanide leaching. As ores differ greatly, the flowsheet needs to be tailored for the deposit in question. The process design is initially based on existing knowledge and then on experimental results. The amount of information available in journal articles and industry reports concerning the processing of gold ores is large and increases continuously. Therefore, the challenge is not the task of acquiring knowledge, but rather the task of managing, classifying and performing comparative analysis of the available information. Efficient exploitation of the existing information aids the professional in defining the needed experiments for developing a process flowsheet for an ore of interest, and in consequence of that, achieve bench and pilot scale experiments sooner. Additionally, rapid financial analysis and cost evaluation of possible flowsheets can be made more attainable through effective comparison techniques. It is well known that ore mineralogies and composition often change within the same deposit. If these variations are known before planning the initial processing plant, comparing possible processes for the different mineralogies in the deposit can lead to a compromise that remains more feasible over time.

Modelling all facets of a processing plant with a vast number of straightforward rules and deterministic equations is highly challenging, as the available data is often incomplete and fuzzy (Rintala et al., 2012, 2015). Instead, the target of this study is to develop a software system that is able to give starting points for gold ore process design by helping the user to remember and compare previously successfully applied processing options on similar

Abbreviation: CBR, case-based reasoning.

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mining sites (Sauer et al., 2013, 2014). To develop such a decision support method, systematic knowledge formalisation is required (Kolodner, 1992).

The three most prominent reasoning methodologies available to create a decision support system are rule-based, case-based and model-based reasoning. Of these three, only case-based reasoning (CBR) is able to handle incomplete and fuzzy knowledge in a way suitable for recommending hydrometallurgical process alternatives (Rintala et al., 2011), and was therefore chosen as the reasoning methodology for this study. CBR has already been applied in various fields of engineering and process design. To name a few examples, Vong et al. (2002) have utilised CBR to support hydraulic production machine design, and Seuranen et al. (2005) have studied how to develop a method for recommending feasible separation process sequences and a separation process structure in chemical technology.

CBR uses the knowledge of past problems, cases, and predicts the likely outcome or applicable solution to a current problem. It performs this prediction based on the knowledge stored in previous cases which are gathered in a case base (Aamodt and Plaza, 1994; Richter, 1998). The knowledge is stored in the case's various attributes, such as pH, chemical formula, price, location, symptom, colour, etc. The current problem is formulated into a case by defining its attribute values and is referred to as the query case.

When using the CBR system, a user makes a query by entering values for each attribute and then the system retrieves cases from the case base organised by their similarity with the query. These similarity measures get values between 0 and 1, the former denoting that the query case and retrieved case are completely dissimilar and the latter indicating that they are identical. The total similarity (global similarity) between case and query is a result of the combination of attribute specific similarities (local similarities) by applying a suitable amalgamation function. When a case consists of n attributes, the global similarity, *Sim (q,c),* between query *q* and case *c* in the case base is calculated as the weighted sum of the attribute specific local similarities according to Eq. (1) (Stahl and Roth-Berghofer, 2008):

$$Sim(q,c) = \sum_{i=1}^{n} \omega_i \cdot sim_i(q_i, c_i) \tag{1}$$

Here sim_i and ω_i denote the local similarity measure and the weight of attribute *i*.

The aim of this research is to construct and study the functionality of a CBR system, designed to recommend possible processing flowsheets for a gold ore of interest. The CBR methodology is applied to compare and rank process alternatives based on similarities between ore properties as defined by the selected nine attributes. Additionally, the constructed CBR system is tested through preliminary retrieval tests and its functionality is evaluated against the expertise of senior level hydrometallurgical experts.

2. Methods

This section describes the construction of the CBR system, methodology of the retrieval tests and interviewing techniques applied during knowledge acquisition.

2.1. Knowledge formalisation

The knowledge formalisation described in this paper was performed using the open source similarity-based retrieval tool myCBR in its latest version 3.0 (myCBR, 2012). The myCBR tool offers a set of graphical user interphases (GUIs) called myCBR workbench, which can be employed for rapid knowledge modelling and prototyping of CBR systems (Stahl and Roth-Berghofer, 2008). This specific CBR tool was selected due to its various useful functionalities such as the possibility to model several local similarity measures for one attribute and then select which one is used in the retrieval step.

2.1.1. Defining case attributes

At the beginning of knowledge formalisation, the relevant entities in the domain need to be identified, as well as their relationships with each other. In this study, the relevant entities were the mineralogical properties of gold ores. Marsden and House (2006) have suggested that after determining the gold mineral type, the ore composition, especially the concentration of gold, other valuable minerals, and minerals detrimental to processing, must be determined prior to gold process design. They also discuss the importance of gold grain size distribution and liberation characteristics of valuable minerals. In this study, nine attributes: *Ore type*, *Gold ore grade*, *Gold distribution*, *Gold grain size*, *Sulfide present*, *Arsenic sulfide*, *Copper sulfide*, *Iron sulfide* and *Clay present* were modelled.

Gold mineral type, referring to the most general description of the ore, such as "*Free milling*" or "*Silver rich*", and gold concentration, or *Gold ore grade*, were relatively straightforward to model into attributes. Other valuable minerals, such as silver, were not seen being as characterising as gold with regards to process design and profitability. Overall mineralogical composition is also important, but significantly more complicated to model into attributes. However, some minerals are more influential than others. The flowsheet design is significantly different for sulfidic gold ores compared to other types, such as free milling ores, because sulfides consume cyanide during leaching. Therefore, three mineral attributes were selected to describe the sulfidic mineralogy of the ore: *Arsenic sulfide*, *Copper sulfide*, and *Iron sulfide*. Additionally, a simple attribute stating the presence of sulfides, without determining the kind of sulfidic mineral was included in the model. Another aspect of ore composition that affects the process design is the presence of clay; hence, an attribute *Clay present* was included in the system. Clay minerals reduce the gold dissolution rates, whether directly associated with the gold, or just present in the ore. Clays tend to hinder the cyanidation process for example by forming impermeable coatings over the surface of the gold which develop after grinding (Gasparrini, 1993). Gold grain size distribution is often described rather vaguely in literature with terms such as "Fine grains". It was however included in the model, despite the possible loss of information related to its modelling. The liberation characteristics of all valuable minerals affect the processing methods, but gold was seen as the most defining. Therefore, the attribute *Gold distribution* was formulated to model the mode of gold occurrence as either "*Free*" or "*Enclosed in mineral*".

In conclusion, the following attributes were selected to be modelled in the first version of the CBR system: *Ore type*, *Gold ore grade*, *Gold distribution*, *Gold grain size*, *Sulfide present*, *Arsenic sulfide*, *Copper sulfide*, *Iron sulfide*, and *Clay present.*

2.1.2. Case representation

Attribute-value pairs were selected for case representation, describing the mineralogy of an industrially utilised gold ore/concentrate. In myCBR the user can select from several attribute data types, which indicate the nature of the attribute. Examples of data types are numerical values and symbolic values, such as names of substances. The attribute types employed in the built system were symbols, Boolean, and floating point numbers. The attributes and their respective data types are presented in Table 1.

The flowsheets related to the ores in the case base were also gathered to be used as starting points for process design for the ore of interest i.e. the queried ore. The flowsheets were formalised into a separate data base, where the user can examine them. Sim-