Case-based Reasoning Application: Selection of Cyanide-free Gold Leaching Methods

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Abstract. Gold is a highly valued metal, mined and processed around the world by using highly toxic cyanide as a leaching agent. Environmental awareness is however driving change towards cyanide-free methods. The challenges arise from the vast variety of ores, complexity of gold metallurgy and the several different options for cyanide-free leaching. This article discusses a CBR tool designed to conveniently compare previously conducted research results on cyanide-free gold leaching. Such a tool would ultimately aid the user in finding research articles utilizing similar raw materials ranging from ores and concentrates to secondary materials. Previously the authors have constructed a preliminary knowledge model for this purpose and here we propose several possibilities and methods of developing the model further.

Keywords: Case-based reasoning, Gold leaching, Cyanide-free gold extraction

1 Introduction

Gold can be found in nature as almost pure gold nuggets, but predominantly gold is extracted from various types of gold ore by using cyanide leaching [24]. Cyanide has been the reagent of choice due to its effectiveness and relatively low cost, but its toxic nature is driving development of new, environmentally safer, methods [16]. Only one cyanide-free gold process is in industrial use [7], while more than 20 methods are regarded as somewhat promising [16], [18], [34]. Because ores differ greatly, one cyanide-free process will not be universally applicable to all types. Therefore, a researcher aiming to find a cyanide-free option for their particular raw material needs to conduct great amounts of literary research in order to narrow down the possible leaching agents and to define process parameter values for later process optimization.

In order to make this research and decision making process more efficient, we have begun developing a tool using case-based reasoning (CBR) [21]. The tool utilizes a database of previous research cases that are then compared to the current problem. In this case, the problem is the gold ore's characteristics. A preliminary database and knowledge model have already been built and the purpose of this article is to discuss

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future possibilities of improving this preliminary model. Ultimately, the aim of this project is to produce a tool that would enable metallurgical researchers both in academia and industry to easily look for cyanide-free alternatives for their specific raw material while considering any restrictions they might have regarding the gold processing route and lixiviant used.

2 Background

2.1 Case-based Reasoning for Metallurgical Applications

The CBR methodology is based on comparing a current problem to previous problem-solution pairs. A formalized problem is used as a query case as most similar problems are retrieved from a case base. Either one or more of the solutions to the most similar problems are then reused and often revised to best suit the original problem. This creates a new problem-solution pair that can be retained in the case-base, thus improving its functionality. [1]

Several CBR tools have been developed for specific metallurgical applications where the process is monitored in order to predict later conditions. As an example, an application has been developed utilizing process information, such as the amount of different added materials and processing time as case attributes for predicting the temperature development of molten steel during the refining process [10]. Alternatively, the amount of a certain substance can be predicted over time. In metallurgical processes various chemical reactions affect the final concentration of elements making process control a complex system. Therefore, CBR methods have been developed to predict, for example, the phosphorous [22] or carbon [11] content of the processed material.

The nature of these applications is very different from selecting a new method for treating a certain gold containing raw material. The most distinct difference is that in the process specific applications the cases are created on site by measuring process parameters, as opposed to when designing a new process, the cases need to be gathered from various different sources. However, CBR has been shown to be suitable for metallurgical process selection due to, for example, its flexibility regarding incomplete input data [32,33].

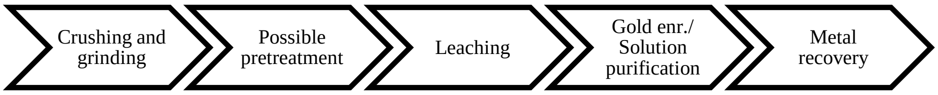
A CBR knowledge model has been built for selecting whole process chains of conventional cyanide leaching [31]. The same software, myCBR 3.0[1], will be utilized in building the present model for cyanide-free leaching, but the fundamentals of the two tools are very different. While the tool for cyanide process chains compares only ore attributes and gives whole process chains as an answer, the present work will ultimately compare also the desired processing parameters and the diversity of the solutions, i.e. the leaching methods, is much wider.

[1] http://mycbr-project.net/

2.2 Gold Processing

The governing method for producing gold from ore is through the conventional cyanide leaching process. The general, simplified, flowsheet of the process is illustrated in Figure 1 [24].

Fig. 1. A simplified flowsheet of gold leaching processes [24]



First, the ore is crushed into a smaller particle size in order to expose more of the gold inside the ore particles. Some ores require a pretreatment such as roasting or pressure oxidation for the gold leaching step to be effective. After the ore is treated and ready for the leaching step, it is immersed in an oxidative cyanide solution, where gold is dissolved into the solution while the side rock of the ore remains solid. This produces a pregnant leach solution (PLS), which concentrated in various ways to increase the gold content. Final recovery of gold is most commonly carried out by gold reduction on to zinc particles (cementation by the Merrill-Crowe process) or by applying electrical current, both methods forcing the dissolved gold back into its solid form. [24]

2.3 Cyanide-free Gold Leaching Methods

As mentioned, there are several cyanide-free gold leaching methods under development. For example, chloride [23], thiourea [8], glycine [28] and bromine-bromide [35] are showing promising results with regards to gold extraction. However, the profitability of most cyanide-free methods are still considered challenging due to the early stage of technological development [18] and inability to control the leaching processes [16]. Additionally to the leaching step itself, also new solution purification, concentration and recovery methods need to be developed for the new processes.

The previously developed knowledge model only included cases where either chloride or thiosulfate were the leaching agent [21], but the case base will be expanded in this regard as the project advances.

Additionally, the cyanide-free leaching methods have more constraints, based on the ore- product-characteristics and the individual processing steps applied. This increased complexity of the cyanide-free leaching processes need to be reflected in a more complex knowledge model to be applied in the CBR system for process selection in this domain.

3 Developing the Knowledge Model

The following sections discuss how the previously constructed knowledge model [21] could be improved as research on this topic continues. We do so by following the overall process of the construction of the knowledge model and discussing possible improvements for each step of the process. We start with the modelling of the case structure, by selecting attributes and their value ranges and then continue to review the cases in our knowledge model and discuss possible adaptations and additions to the similarity measures within our knowledge model.

3.1 Adding Attributes

In the authors' previous work, scientific review articles about cyanide-free gold leaching methods [16], [18], [34] were analyzed and hydrometallurgical researchers were interviews in order to select attributes to be included in the preliminary knowledge model. The final selection of ore and process attributes is presented in Table 1. [21]

Table 1. Selected attributes for the preliminary knowledge model [21]

Attribute	Type of attribute
Method	Symbol
Mineral 1	Symbol
Mineral 2	Symbol
Gold content [g/t]	Floating point number
Extraction [%]	Floating point number

Method implies which leaching method, thiosulfate or chloride, was used. *Mineral 1* and *Mineral 2* are the most and second most abundant minerals in the ore, excluding barren quartz, because practically all ores contain quartz [24]. If the gold was to be reported occurring within the quartz minerals, then it would be included. *Gold content* expresses the amount of gold in grams per ton of raw material. *Extraction* is a term used to describe the percentage of gold that was successfully leached during the experiments.

While these attributes were seen as the bare minimum for building the knowledge model, the model's functionality and possible applications will benefit greatly from additional attributes. For example, the researcher has a very complicated ore and two governing minerals can't possibly describe it's behavior or they have some restrictions regarding the processing parameters such as they can't use temperatures above 80 °C, then it would be beneficial to have more attributes describing the cases.

Since the selection of the attributes in Table 1, more interviews have been done, more than tripling the amount of experts that have answered the survey. During both instances, we used a semi-structured interviewing technique [5], where the questions were predefined open questions that were asked in the same order and no additional questions were asked. The questions within the interviews were as follows:

- Imagine you were designing an experiment series for chloride leaching. If all information from previous research articles was thoroughly organized, what knowledge and parameters would you compare for
    - free-milling ore?
    - refractory ore?
- What parameters would you like to use for excluding cases from the comparison?
- If you were designing a thiosulfate experiment instead, would it change your answers to question 1 and 2?
- There is a preliminary model that compares previous research cases based on attributes in this example:

Method	Mineral 1	Mineral 2	Gold Content
Chloride	Ankerite	Muscovite	1.5
Thiosulfate	Arsenopyrite	Pyrite	56
Thiosulfate	Pyrite		94.63

- What attributes would you add to the list, in order to better describe the ore?

The results of the additional interviews will be combined with the original set, resulting in altogether 23 interviewing results. The appearances of different attributes will be quantified and the ones mentioned most frequently will be incorporated into the knowledge model when possible.

3.2 Expanding the Case Base

Currently, the preliminary case base consists of 24 cases, gathered from 20 scientific articles [2,3,4], [6], [9], [12,13,14,15], [17], [19,20], [25,26,27], [29,30], [36,37,38]. The case base will be expanded by classifying potential case sources through automated natural language processing. This will be conducted using an ANNIE (A nearly new information extraction) application within the GATE[2] natural language processing architecture. The cases can then be formalized by searching the relevant attribute values manually from the case sources. These can then be added to the case base, enhancing the model's overall performance. Subsequent development in this regard could be semi-automatic case extraction from the sources. However, further refinement of the extraction application needs to take place and the resulting cases would still need to be authenticated and possibly completed manually.

In order to improve the model even further, the scope of the case acquiring will be extended beyond the two methods, thiosulfate and chloride, and also expand its focus from natural raw materials to secondary sources such as electronic waste. Expansion of the scope should result in a significant increase in the amount of cases in the database.

[2] http://gate.ac.uk/

This would probably lead to higher similarities between queried raw materials and the materials described in the case base, but addition of attributes will more than likely reduce the similarities between cases.

3.3 Calculation of Similarity Values

During the construction and testing of the previous model, several issues in need of correction were detected in the way the knowledge model calculates similarity values between cases. Most development work will go towards formalizing and modelling the mineralogy of ores. The subject is complicated to formalize as the amount of different minerals present in an ore body can vary greatly between or within deposits. Additionally, the similarity between two minerals can be high in one leaching process, but low in another process. In other words, the similarity between two minerals is not a constant, but differs depending on the leaching method.

Currently, the model compares the most abundant mineral, *Mineral 1*, with only the *Mineral 1* values in other cases. In the event where the two most abundant minerals are the same, but in opposite proportions, the model returns a low similarity even though the materials are in practice very similar. The model built for cyanide based processes [31] utilized a method where the user would indicate the amount of certain mineral types, but also this approach has its shortcomings; for example, if the ore contains more than one mineral of the same type, the user has no way of incorporating both minerals in the query.

One challenge in modelling the mineralogy is the fact that the possibility of querying a certain mineral should not be restricted by the minerals already in the case base. However, there are thousands of minerals, with more discovered continuously, and formalizing all of them for the calculation of similarity measures would not be reasonable.

Since the preliminary model includes only two different leaching methods, the *Method* attribute has so far been given a value of 1 or 0, representing equal or different value. The expansion of the case base brings the question of similarity values between different leaching methods. Some leaching methods can be seen as more similar than others and some can even be combined. This will call for thorough investigation of the characteristics of all available gold leaching methods.

The model will expand significantly with new process attributes, such as temperature, pressure, pH, reagent consumption, solid-liquid ratio and leaching agent concentration. Formalization techniques need to be defined for these attributes and local similarity measures need to be assigned. While the amount of the attributes increases, the usability of the system still needs to remain on a tolerable level.

4 Summary

While the use of toxic cyanide in gold extraction processes continues to be the norm, new cyanide-free leaching method are being developed for gold production. In order to aid researchers in experimenting on these methods, a CBR based tool is being developed for comparing previous experiments. A preliminary knowledge model and case base have been constructed, but several aspects of the tool will be developed further in the future. The case base will be expanded through combined automated and manual case extraction and the way of formalizing ore mineralogy will be reconstructed. Additionally, new attributes will be incorporated along with their similarity models.

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