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APPLICABILITY OF PUBLISHED EXPERIMENTAL WORKS AS A KNOWLEDGE SOURCE IN RECOMMENDATION OF GOLD ORE PROCESSING WORKFLOWS

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Abstract: The experimental work is the most time consuming and expensive part of the process design. A case-based reasoning (CBR) methodology can be used to assist in the process design. *Auric Adviser* is a CBR system under development for recommendation of gold ore processing workflows. In *Auric Adviser* the knowledge in gold ore processing is represented in two models. The first model holds the knowledge needed to recommend process chains already used in industry. The second knowledge model is intended to recommend the most efficient unit processes based on research results. The objective of this study was to analyse the information richness of journal articles and other publications concerning single process steps of gold extraction. The aim was to study the applicability of these publications as a source for the second *Auric Adviser* knowledge model. In this study, 25 publications concerning leaching of gold were analysed and information was extracted in a case base. The case base was taken as either a process or experimental description with clearly defined differences to other descriptions. In total, 218 cases that described results of gold leaching were extracted from the sources. The analysis of descriptions showed that the knowledge necessary for design the second *Auric Adviser* model can be elicited from journal articles and other publications concerning single process steps. The trends in the case description were that the gold content and process outcome were usually well described. Nevertheless, the information richness varied in descriptions of raw materials, experimental arrangements but the results were often missing details. The incompleteness of information causes challenges in the process comparison although it does not prevent the CBR system to work.

Keywords: *gold ore, leaching, case-based reasoning, process development*

Introduction

The availability of knowledge is not an issue for today’s expert designing gold ore processes as the amount of knowledge available in forms of journal articles and industrial reports is large and increasing continuously. It can be seen from Tables 1 and 2,

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where the numbers of publications found in the Scopus data base (scopus.com) by several search terms are listed. The terms were searched within article title, abstract and keywords. A selected subject area was Physical Sciences and all document types were included. From Table 1 it can be seen that half of publications concerning gold ores are published within last 14 years.

Table 1. Number of publications about gold ore processing (source: scopus.com, accessed: 10.10.2014)

Terms used in the search	Published in years	
	1960-2014	2000-2014
gold AND ore	11978	6561
"gold ore"	3715	1563
gold AND refractory	998	533
gold AND refractory AND pretreatment	153	97
gold AND refractory AND preoxidation	11	6

Table 2 shows the increasing rate of research on treatment of refractory gold ores. Instead of the availability of knowledge, the facing challenge for each expert is to remember, classify and perform the comparative analysis of available knowledge.

Table 2. Number of publications about refractory gold ore processing (source: scopus.com, accessed: 10.10.2014)

Terms used in the search	Published in years	
	1960-2014	2000-2014
gold AND refractory AND roasting	118	51
gold AND refractory AND bioleaching	112	63
gold AND refractory AND oxidation	390	211
gold AND refractory AND oxidation AND sulfide	205	110
gold AND refractory AND oxidation AND oxygen	65	36
gold AND refractory AND oxidation AND "nitric acid"	8	16
gold AND refractory AND oxidation AND chlorine	18	6

Development of new hydrometallurgical processes requires extensive, time consuming and often expensive experimental work. To enhance the development phase utilisation of existing information is important. The published sources can provide anything from large reviews to minute details and the challenge is how to use this information most effectively. Efficient exploitation of the existing knowledge helps to select needed experiments for specific processes precisely. A case-based reasoning (CBR) methodology has been tested and found to be suitable for recommendation of gold ore processing workflows (Rintala et al., 2011a, 2011b; Sauer et al., 2013, 2014).

It can help to assist with the tasks to remember, classify, recommend and perform the comparative analysis of the knowledge on gold ore processing. It is a decision support method, which is very similar to the way human reach decisions or solve problems. It solves new problems by using previously successful solutions to similar problems and adapting proven solutions to a current problem based on the knowledge stored in previous cases (Aamodt and Plaza, 1994; Lenz et al., 1998). The main benefit of CBR over other decision support methods is its ability to work with incomplete and fuzzy data (Rintala et al. 2011a, 2011b; Sauer et al., 2013).

In this work we extracted over 200 descriptions of experimental work about gold dissolution and processing of gold ore or concentrate from various sources. The information content of these descriptions was analysed and applicability of published experimental work as a knowledge source in the recommendation of gold ore processing workflows by the CBR methodology was studied.

Auric Adviser – a CBR system for recommendation of gold ore processing workflows

The CBR system under development is called *Auric Adviser* (Sauer et al., 2013, 2014). In *Auric Adviser* the knowledge in gold ore processing is represented as a two-stage approach. Two knowledge models serve each of two aspects of the approach. The first model presented by Sauer et al. (2013, 2014) holds the knowledge needed to recommend process chains already used in the industry. The second knowledge model is intended to recommend the most efficient unit processes based on research results. The suitable cases are retrieved from the case base using a similarity between new (query) and existing cases. The similarity between query q and case c is calculated as (Stahl and Roth-Berghofer, 2008):

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

where sim_i and ω_i denote local similarity measure and weight of attribute i, respectively, Sim represents the global similarity measure. The similarity is computed in an interval between 0 and 1 [0,1], which represent most dissimilar and identical values, respectively.

The knowledge for the first *Auric Adviser* model was formalised using the open source similarity-based retrieval tool myCBR in its latest version 3.0 (myCBR, 2012). After knowledge formalisation 25 cases were extracted from descriptions of existing gold mines (Marsden and House, 2006). A test run of the retrieval of cases from the first knowledge model is shown in Table 3.

Table 3. The best (1–3) and the worst (lowest Sim) matching cases retrieved from the *Auric Adviser* case base

Attribute	Query	1st	2nd	3rd	Lowest Sim (q,c)
Gold ore grade	12 g/Mg	8.5	4.7	5.0	70.0
Ore type	refractory iron sulphide	refractory iron sulphide	refractory iron sulphide	refractory iron sulphide	silver-rich
Gold distribution	grain enclosed in mineral	colloidal particles in solution	grain enclosed in mineral	grain enclosed in mineral	Unknown
Gold grain size	submicron sized	submicron sized	fine	submicron sized	Unknown
Iron sulphide	Pyrite	pyrite	pyrite	pyrite	Pyrite
Clay present	Yes	yes	yes	unknown	No
Sim (q,c)		0.86	0.85	0.82	0.20

When a process is designed for either a new gold ore or concentrate the expert can post a query to *Auric Adviser* for searching the existing process designs for similar raw materials. Several attributes can be used to characterise the raw material in the study. The test query consisted of the following attributes: gold ore grade is 12 g/Mg, ore type is refractory iron sulphide, gold distribution is grain enclosed in mineral, gold grain size is submicron sized and iron sulphide is pyrite. Table 3 shows how *Auric Adviser* retrieves the best matching cases according to the query from the case base by using the similarity (Eq. 1).

The best matching case is the Goldstrike mine in Nevada, United States. Gold is present primarily in the colloidal form within pyrite and marcasite mineral grains as submicron sized inclusions. The ore contains some clay minerals. The ore is processed by pressure oxidation. After crushing, grinding and thickening slurry is pretreated using an acidification process. Then, the slurry is heated using two stages of splash heating and fed into six autoclaves. Leaching is performed by agitated cyanide leaching and carbon-in-leach (CIL) and gold is recovered from the carbon eluate solution by electrowinning (Marsden and House, 2006).

The second best matching case is the McLaughlin mine in California, United States that was closed in 2002. Fine-grained gold was associated with fine-grained sulphide minerals. Among other reasons refractory properties of the ore were caused by presence of clays. The process applied was acidic pressure oxidation. Leaching was performed by agitated cyanide leaching and carbon-in-pulp (CIP) and gold was recovered from the carbon eluate solution by electrowinning (Marsden and House, 2006).

The third best matching case is the Lihir project that consists of two deposits in Lihir Island, Papua New Guinea. Gold is locked as submicron particles within a pyrite matrix. Also in this case ore is treated by pressure oxidation, followed by agitated cyanide leaching and CIL. Then gold is recovered from the carbon eluate solution by electrowinning (Marsden and House, 2006).

After analysis of the cases the next step is to test a new raw material under process conditions that are used in the retrieved cases, beginning from conditions of the best matching case and if the process performance is not acceptable, tests are performed in decreasing order of similarities of the retrieved cases. Here almost the same process was applied for three most similar cases to the query. This indicates that the relevant first experiments for the new raw material are pressure oxidation test by parameters used in three best matching cases. The second *Auric Adviser* model can be used to define the experimental design, as it is intended to hold the knowledge of the specific treatments.

Material and methods

The aim of this paper was to study the applicability of scientific publications as knowledge source for the second *Auric Adviser* model. The target of knowledge formalisation for *Auric Adviser* is to efficiently exploit the knowledge from journal articles and other publications to propose and develop process steps for gold processing.

As described earlier, in *Auric Adviser* the knowledge of gold ore processing is represented as a two-stage approach. The first knowledge model recommends process chains already used in the industry. The second knowledge model is intended to recommend the best treatments based on research results. The cases are represented as treatments on either specific raw material or processing stage. The treatments are unit processes that are seen as actions that change the system state. For example, leaching is a treatment that takes solid raw material and leachate as the input and results in pregnant solution and residue as the output. The treatments are defined by listing the preconditions and effects of the unit processes. The treatment cases are stored in the case base and the case-based reasoning methodology is used for the case retrieval according to the user query (Fig. 1).

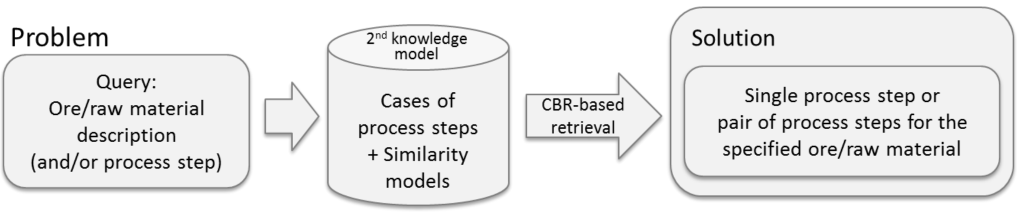

Figure 1. Operation of second *Auric Adviser* model

The process of encoding knowledge of CBR system in case representation and in global and local similarity measure is called knowledge formalisation. First, relevant categories in a domain and their relationships with each other are identified. Then, characteristics and important attributes are established for each category and the form of case representation is determined. After the relevant entities are identified, the next step is to find suitable data types and value ranges to represent these attributes. Then, the similarities between attributes are modelled by taxonomies, comparative tables and mathematical functions (Aamodt and Plaza, 1994). The case-based reasoning is heavily dependent on the structure and content of its collection of cases. It must be decided what to store in the case and how the case memory should be organised and indexed for effective retrieval and reuse. An appropriate structure for describing the case contents can be also found. There are the central questions to be answered in order to use published hydrometallurgical experiments as the cases in the CBR application. In this study, the case was expected to include description of raw material that was studied and description of the solution chemistry and experimental arrangements that were used, as well as process outcomes.

To analyse how detailed the experiments about gold extraction were published, 17 journal articles and 8 other publications were chosen to be analysed and the information of used process and its details were collected in a case base.

Table 4. Analysed publications and amount of cases extracted

Journal articles/ Other publications	Number of analysed publications	Amount of cases extracted	References
Hydrometallurgy	6	47	Crundwell and Godorr, 1997; Breuer and Jeffrey, 2002; Chandra and Jeffrey 2004; Breuer et al., 2005, Dai and Feffrey, 2006; Feng and van Deventer, 2007
Minerals Engineering	2	31	Groudev et al., 1996; Aylmore and Muir, 2001
Mining informational and analytical bulletin (scientific and technical journal)	6	69	Vorobjev et al., 2003; Zuboreva, 2006; Gurman and Jatlukova, 2007; Rubcov, 2007; Zuboreva, 2007; Gurman, 2009
Doklady akademii nauk respubliki Tadzhikistan	1	12	Zinchenko et al., 2010
Vestnik KRSU	1	3	Vorobjev et al., 2010
Izvestiya Chelyabinskogo Nauchnogo Tsentra (UrO RAN)	1	1	Chekushin and Oljnikova, 2005
Master thesis	1	20	Fairley, 1998
Books	3	31	Chernjak, 1987; Chungaev, 1987; Meretukov, 2008
Bulletin	4	4	Demetjev et al., 2000, 2005; Emeljanov, 2004; Haavanlammi et al., 2010
TOTAL	25	218	

The publications were collected by using publication databases, such as Science Direct, Scopus and Google Scholar. In the initial search round words “leaching” and “gold” were used, and in the second search round words “refractory” and “ore” were added. The analysed publications and amount of cases extracted are listed in Table 4.

The information given for one case was evaluated and stored using as many categories and details as possible. It was often possible to extract several cases for analysis from one publication. The case was taken as either process or experiment description with clearly defined differences to other descriptions. In total 218 cases were extracted, which included 40 cases, where either gold or gold containing alloy was leached and 178 cases which described leaching of either ore or concentrate. From the latter ones, 86 cases were described as leaching of the refractory gold ore. To determine the attributes that were used to describe the cases in publications the information given for one case was stored using as many details as possible.

Results and discussion

The attributes that were used to describe the case in the analysed publications were arranged in four categories: raw material, solution, process parameters and process performance. The found attributes are presented in Table 5. Table 5 shows that there is varying number of attributes used to describe these four categories. These attributes can be used in the similarity calculation of the CBR system recommending gold ore processing workflows although none of the cases covered information on every attribute presented in Table 5. Especially the attributes describing the raw material were often missing details.

Table 5. Attributes that were used to describe cases in analysed publications

Raw material	Solution	Process parameters	Process performance
Minerals	Ligand	Pumping rate	Reaction rate
Pre-treatments	Stabilisator	Solids in slurry	Recovery
Pre-treatment period	Oxidant	Solid-to-liquid ratio	Reagent consumption
Particle size	Catalyst	Reactor volume	
Au concentration		Solution volume	
Other valuable metals		Agitation method	
Other elements		Stirring speed	
		Gas bubbling	
		Dissolved oxygen	
		Temperature	
		pH	
		Oxygen partial pressure	
		Retention time	

The most important attributes for the second *Auric Adviser* model were: gold concentration, solution chemistry in details, temperature, pH, reagent consumption and process outcome. The percentages of cases covering information of these attributes are shown in Table 6. The gold concentration of studied sample was usually reported. The process outcome, like either reaction rate or recovery of gold, was described in the majority of cases as well. The journal articles very often contained information on the solution chemistry and pH than other publications. The temperature and reagent consumption were sparsely reported in all sources.

Table 6. Analysed cases covering information of listed attributes

Attribute	Journal articles, %	Other publications, %	All publications, %
Au concentration	83	62	80
Solution chemistry in details	71	47	65
Temperature	49	47	49
pH	67	38	60
Reagent consumption	20	24	19
Outcome of the process	82	98	86

In the analysis of cases concerning either ore or concentrate a higher number of attributes, such as origin and chemical analysis of the studied sample are important. The results are presented in Table 7. The gold concentration of studied sample was usually described as well as the process outcome, temperature and reagent consumption were sparsely reported in all sources.

Table 7. Cases concerning either ore or concentrate covering information of listed attributes

Attribute	Journal articles, %	Other publications, %	All publications, %
Au concentration	95	56	84
Origin of the ore/concentrate (deposit etc.)	62	46	57
Chemical analysis of the studied sample	12	42	20
Solution chemistry in details	65	48	61
Temperature	40	44	41
pH	70	42	62
Reagent consumption	25	19	23
Outcome of the process	98	98	98

The experimental arrangements were usually well described in the journal articles. However, the chemical analyses of studied samples were described more often in other publications than journal articles. In the journal articles the material description was frequently limited to reporting the origin of either ore or concentrate. This is problematic from perspective of knowledge applicability in recommendation of gold ore processing workflows as well as from perspective of repeatability of the study. In some cases it may be possible to estimate the character of ore on the basis of geology of the ore region by using available ore and mineral databases (Pietarsaari 2011). The information on geology of the area, such as analyses of bore samples can be found from these databases. However, the information may not be up to date. Old drill samples may not represent the ore mined from the site today. The analysis of the existing information sources showed that the knowledge necessary to design the second *Auric Adviser* model can be elicited from the journal articles and other publications concerning single process steps. The attribute sets, such as shown in Table 5, can be used to describe the treatment performance. However, in some cases the sources did not contain enough information to create a well-defined case. In the next phase of the research the second *Auric Adviser* model will be formalised using the open source similarity-based retrieval tool myCBR. After that, the applicable cases from this study can be transferred to the case base of *Auric Adviser*.

Conclusions

The *Auric Adviser* model helps to select starting point for experiments. The first *Auric Adviser* knowledge model can be used to give ideas of existing process designs for similar raw materials. The second *Auric Adviser* knowledge model is intended to be used to define the experimental design. After initial tests the factorial design can be used to design full set of experiments. In this research the applicability of scientific publications as a source for the second *Auric Adviser* model was studied. To analyse how detailed the experiments about gold extraction are published, 17 journal articles and 8 other publications were chosen to be analysed and the information of used process and its details were collected in the case base. In total, 218 cases were extracted from various publications. To determine the attributes that are used to describe cases in publications the information given in a single case was collected using as many details as possible. The analysis of the case descriptions showed that gold content and outcome of the process were usually well describe, whereas the process details were not.

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