Physicochem. Probl. Miner. Process. 46(2011) 229-242

journal homepage
www.minproc.pwr.wroc.pl/journal/

Physicochemical Problems of Mineral Processing

Index No. 32213X ISSN 1643-1049

Lotta RINTALA *, Kristian LILLKUNG*, Jari AROMAA*

THE USE OF DECISION AND OPTIMIZATION METHODS IN SELECTION OF HYDROMETALLURGICAL UNIT PROCESS ALTERNATIVES

Received April 12, 2010; reviewed; accepted August 12, 2010

The hydrometallurgical process routes development has traditionally been made based on personnels' experiences and preferences. This tacit knowledge has been very difficult to communicate to other people. For this reason an attempt has been made to develop a tool that could be used as a selection tool or a decision support method when making process route decisions. A description of the decision problem is the most important element in decision making. That is discussed via human decison making and decision support and optimization methods. In addition, a typical hydrometallurgical process chain and decisions made in different stages at the chain are discussed. The main focus in this study is to establish what kind of tool would help in the rough selection between the different unit processes. The optimization of the process chain would be the next stage of development work but that is not discussed here.

keywords: hydrometallurgical unit processes, decision and optimization methods, human decision making

1. INTRODUCTION

When a new hydrometallurgical process is designed, decisions and comparison between process alternatives are made by human. This is somehow ineffective way since there is inexpensive and effective artificial intelligence available. There are not many cases where computers can beat the intelligence and creativity of human. But when the task is to classify and perform comparative analysis by factors that can be described by mathematical models, it is worthwhile to use computers to support the

---

* Aalto University, Department of Materials Science and Engineering, PO Box 16200, FIN-00076 Aalto, Finland. email: lotta.rintala@tkk.fi

decision making. This situation exists exactly when designing a hydrometallurgical process route consisting of different unit processes and their alternatives. When selecting a processing step the number of alternatives is probably between 10 and 100 taking into account different techniques and different process parameter ranges.

There are lot of information and tacit knowledge about suitable processes, but it is not usually easily available. That knowledge should be collected, preferably in numerical form. Then a decision making tool or procedure could be developed. That would enable other people to get access to this information. If the decision making tool could predict the suitable process chain as early as possible, it would help to decrease expensive and time consuming laboratory tests made to new raw materials.

A description of the decision problem is the most important element in decision making. The decision problem must be clearly defined and limited. The decision problem in this study is limited so that process development starts from pretreatment processes of raw material, i.e. grinding, beneficiation or chemical treatment before leaching.

Selection of unit processes and process optimization are very closely connected. The main difference is that process optimization is typically used to mean the variation of certain process parameters in order to achieve as good process output as possible. The emphasis of process selection is on determining, which unit processes would be suitable in general, based on the knowledge of similar cases already accomplished or which have been found to be working in the laboratory scale. Based on the selection process the optimum process parameters cannot of course be discovered. For this reason the selected process routes should be more thoroughly inspected and optimized with proper tools after the selection.

2. HUMAN DECISION MAKING

Human reasoning and decision making depend on many levels of neural operation, some of which are conscious and overly cognitive. The cognitive operations depend on support processes such as attention, working memory and emotion. According to Bechara et al. individuals make judgments not only by assessing the severity of outcomes and their probability of occurrence, but also and primarily in terms of their emotional quality (Bechara et al., 2000).

One factor affecting the decision making is so called decision situation. Decision situation is a broad term including the following (Sage and Armstrong, 2000):

- the objectives to be achieved
- the needs to be fulfilled
- constraints and variables associated with the decision
- people affected by the decision
- the decision options or alternative courses of action themselves
- the environment in which all of these are embedded

– the experience and familiarity of the decision maker with all of the previous.

The decision situation is therefore very dependent upon contingency variables. Some of the most important elements affecting the decision making are shown in Fig. 1.

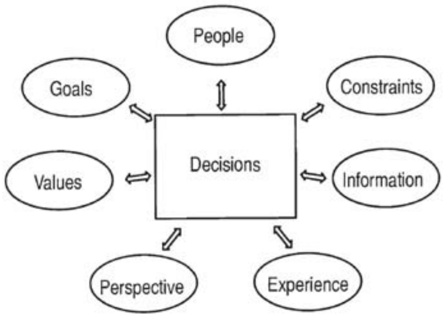

Fig. 1. Key elements affecting the decision making situation (Sage and Armstrong, 2000)

The most important element in decision making should be the goal of the decision, which is the main underlying reason the decision is being made. Besides the goals, there are very often values that the decision should also comply with. These can be personal values or for example corporate values. There are always present also some sorts of constraints like for example maximum available time or cost (Sage and Armstrong, 2000).

Perspectives of the decision maker and other people involved can often be in a major role considering the result of the decision. There are four human rationality perspectives that must always be considered in almost every decision situation: emotional, organizational, political, and technoeconomical. In this report, the focus will be only on technical and economic factors. The use of a certain process might, for example, cause more resistance among the locals (political factor). These kinds of factors may be difficult to evaluate properly with a numerical tool (Sage and Armstrong, 2000).

Previous experience in similar decision situations makes decision making much easier. Through similar experiences, the decision maker is already familiar with the type of problems. These experiences form part of the individual's tacit knowledge. This means that the individual has gained experience to act as an expert and make conclusions without precise qualitative information on which to base the conclusion. Typical for this kind of knowledge is that it is difficult to pass on to others or even express in words.

3. HYDROMETALLURGICAL PROCESS CHAIN

The hydrometallurgical process chain can be roughly divided in three stages (Fig. 2). Pretreatment and leaching stages are separate stages in real processes, but should be considered as a single stage when comparing different process chains. Different types of leaching processes require very different pretreatments, which can raise the costs of certain processes significantly (Hayes, 1985).

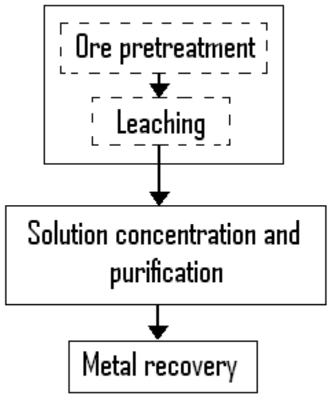

Fig. 2. Three stages of process chain

3.1. HYDROMETALLURGICAL PROCESS CHAIN

The ore pretreatment is needed for enhancing the metal recovery and improving the kinetics of the reactions. The pretreatment processes can be classified in three different broad categories (Hayes, 1985):

- comminution and beneficiation
- chemical changes in the minerals
- structure modification.

Comminution is used to increase the surface area of the ore of certain mass. By increasing the surface area more mineral grains are exposed to solvent. In the leaching process it is not necessary to completely liberate all the mineral grains as long as direct contact between some portion of mineral grain and the leach solution is achieved. The volume of reagent required and the consumption of solvent by the reaction is reduced when the mineral feed is concentrated before leaching. Metal concentrations in leach liquor becomes at the same time higher (Hayes, 1985).

Chemical treatments may be necessary to obtain the metal in a form, which is more easily taken into solution. In most cases this involves pyrometallurgical treatments but also hydrometallurgical processes are possible. Pyrometallurgical processes often result also in a change in microstructure of the minerals (Hayes, 1985).

The reactivity of minerals can be improved also by small changes in the ratio of the elements present in mineral. The various defects in the material can increase the kinetics of the reaction by providing preferential sites for chemical reactions (Hayes, 1985). The dislocations and micro cracks in the mineral enhance the dissolution rates and exposes fresh grains, which would not be otherwise in contact with the liquid.

3.2. LEACHING

In Figure 3 different hydrometallurgical processing techniques are presented. Based on the scale factors the leaching can be done in four alternative ways. The main factors affecting the selection of the leaching process are the grade of the ore, the dissolution rate of the metals and the amount of raw material to be processed. In practice the selection of the leaching process is an optimization problem, where the maximum amount of the metal content is attempted to dissolve in as short time as possible and with as small expenses as possible.

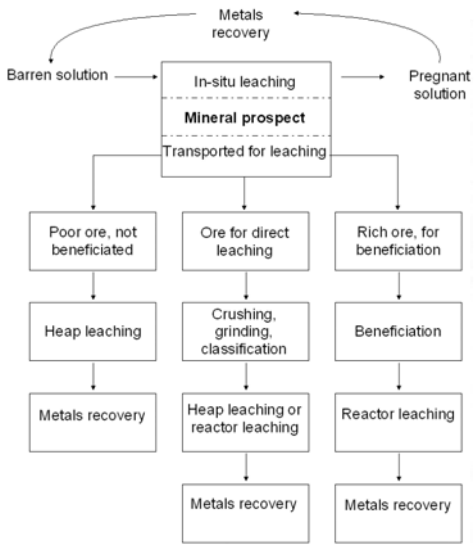

Fig. 3. Hydrometallurgical leaching techniques (Wadsworth, 1987)

As the grade of ore decreases the energy consumption per amount of metal produced increases. For every raw material there is a cut-off grade, which is the lowest grade of ore that can be economically processed. The cut-off grade can be estimated by comparing the earnings of the produced metal with the production costs. Production costs to get metals into solution include mining, crushing, ore beneficiation and leaching, but all the steps are not used in every case. The lower the grade of the ore, the simpler the process has to be and the lower the operating costs have to be.

When choosing the leaching technique, the first decision is whether the ore is transported for leaching or not. If not, the leaching method is the In-situ-leaching, where the ore is not extracted, instead the solvent is pumped into the ore body and the metal containing solution is collected for the metals recovery. In-situ -leaching is used for example in the extraction of uranium.

If the metal is transported for leaching, the second decision is whether to do ore beneficiation. If there will be no beneficiation, leaching is done by heap leaching, where the coarse ore is stacked in large dumps or heap pads. In all heap leaching methods the leaching reagent flows through the ore. If beneficiation is made before the leaching, the choice will be reactor leaching. In the reactor leaching the processed ore is leached in a specifically designed reactor using agitation, temperature, pressure, solvent concentration, etc. to increase the reaction kinetics. The recovery is better in reactor leaching than in heap leaching, but the processing costs increase as well.

3.3. SOLUTION PURIFICATION AND RECOVERY

The objective in the solution purification is to remove the impurities or increase the concentration of the prospective metal. There are lots of hydrometallurgical unit processes available for solution purification, some of them are based on transport of the dissolved element from a liquid phase to another and some of them are based on forming a solid phase (Fig. 4). When choosing a process for solution purification the proper order of alternatives is:

- crystallization, chemical precipitation or liquid-liquid extraction
- cementation or ion exchange
- electrolysis or adsorption.

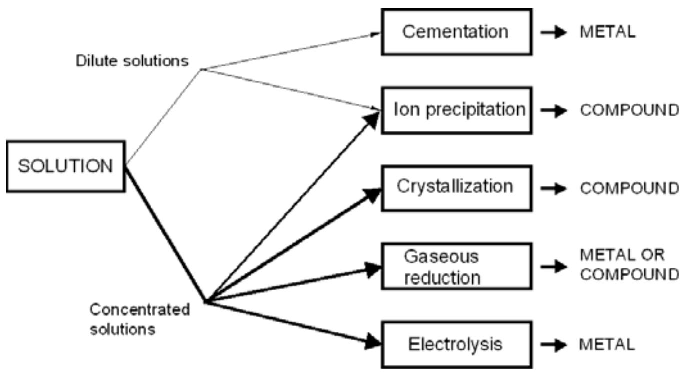

Fig. 4. Different solution purification processes and consisting products

After the leaching stage, impurities in the solvent are removed in the solution concentration and purification stage. In the solution purification the aim can be in transferring the desired metal into a pure solution or removing unwanted metals and anions while the remaining solution is ready for further processing. The used solution purification process depends on the properties of the solution.

Separating the metal from the solution can be done by crystallization, precipitation, cementation or electrolysis. Crystallization and precipitation are based on solubilities and reaction equilibrium, whereas the cementation and electrolysis are based on reduction reaction. Changing the metal from one solution phase to another can be done by adsorption, ion exchange or liquid-liquid extraction and in these methods the metal is bonded temporarily to a transmitting agent.

When choosing the solution purification processes the key factors are the volume of solution and the grade of the metal recovered. Process selection is also affected by the place of the process in the process chain, where the solution purification is done and what is the targeted level of purification. The target level can be determined either by the acceptable level of impurities or by the desired recovery of the wanted metal from the solution.

4. DECISION AND OPTIMIZATION METHODS

At first, it is important to point out the difference between process optimization and decision optimization. In this case, the emphasis is on the decision optimization. The main focus in this study is to establish what kind of tools would help in the rough selection between the different unit processes. The optimization of the process chain is the next stage of development work and is not discussed here. There are two different approaches identified for the decision optimization: decision support tool and optimization. The number of potential mathematical methods that can be used is high.

Decision methods can be classified generally in two different categories, decision making and decision support methods. The former are meant to make decision making as automatic as possible and the latter ones for supporting the decision making process and making it easier. Different methods have been developed for different purposes. Knowing the purpose is essential to achieve the optimum result. Various decision support and decision making methods have different names in different fields although the methods themselves are quite similar. Three different decision support systems have been identified as promising for this kind of use (Sage and Armstrong, 2000):

– Decision tree / Decision forest (DT/DF)
– Multi-criteria decision making (MCDM)
– Case based reasoning (CBR).

In addition to decision methods, there are numerous different optimization methods available. These are mainly useful when trying to search for a minimum or maximum of a function already known. None of the methods is able to achieve the optimum point in every situation. Optimization methods can be divided into traditional and modern methods. The former includes for example the traditional linear and nonlinear optimization. The latter includes for example genetic algorithm, ant colony optimization and neural networks (Rao, 2009). Some of these optimization methods could be fairly used in decision making. These include the following:

– Artificial neural network (ANN)
– Ant colony optimization (ACO)
– Genetic algorithm (GA).

The problem with some of the optimization methods is that they sometimes find only the local minimum so the user has to know the magnitude of the result to verify it. This can be challenging especially when the number of parameters affecting the variable is high (Rao, 2009). Also different methods based on different algorithms may give different results.

5. CHOOSING UNIT PROCESS ALTERNATIVES BY OPTIMIZATION AND DECISION SUPPORT METHODS

When choosing unit processes, the main focus should not be on process optimization right from the beginning as the number of potential unit process chains is high and therefore the number of parameters to be optimized would be high. This would require the models to simplify many things, which would lead to a situation that the achieved optimum could greatly differ from the actual case. Alternatively, the comparison would require a lot of manual labour in modelling the processes and would lead to high calculating capacity demands. One goal of the tool development should be the low need for manual work and moderate capacity demands. By creating a model of every possible process and its variation the optimum process would most probably be found, but the amount of work compared with the achieved benefits would be high. Because of the high level of manual work the usability would be poor and would not bring any substantial improvement to the situation at present.

A better way would be to first narrow down the number of optimizable processes using certain criteria. One alternative would be to create a model that could predict the potential unit processes based on the composition and other classifying properties of the ore or mineral. Process decision about the first pretreatment and leaching stage narrows down the possible unit processes in the later stages. The number of choices of process chains to be simulated should be narrowed down to 3-5. Simulating all the process chain variants is not a realistic option because of the high need for manual work and high calculating capacity demand. One key factor considering the tool is that two different users should be able to get the same answer with the same input data. Also in evaluation of different unit processes the scale has to be considered. One unit process is more usable in a small scale whereas some other is at its best when the material flows are high.

After narrowing down the number of possible process chains the remaining processes should be simulated in a process simulator, such as the HSC Sim by Outotec Oyj (Oyj, 2010). Optimum detailed parameters can then be found and the decision between the process chains can be made based on simulated results.

Different methods for choosing hydrometallurgical unit process alternatives are compared in Table 1. Comparing totally different decision methods is however not straightforward. By pointing out different properties any method can be shown in a more attractive way than the others. For this reason the focus should be on the main topics. Main difference between the methods is the possibility to use database for decision making instead of a function describing the relationships between the different parameters. According to Table 1, it seems that CBR could be the most suitable method for this kind of decision making.

Table 1. Comparison of different decision methods

	Methods					
Properties	ANN	ACO	GA	DT/DF	MCDM	CBR
requires a function to be optimized		x	x		x	
can be used without knowing the exact parameter relations (function)	x			x		x
possibility to form (optimize) process chains		x				
decisions based on a database of similar cases	x					x
weighting of different parameters possible	x	x	x		x	x
possibility to use method with lacking data						x

In the following part we have discussed the suitability of the different methods for the selection of the unit process alternatives more deeply. Firstly the decision methods (Decision tree/forest, Multi-criteria decision making and Case based reasoning) are discussed and secondly the optimization methods (Artificial neural network, Ant colony optimization and Genetic algorithm) are considered.

The Decision tree is a method, which makes data classifying fairly easy. Starting from the root, analysis ends up in the leaf by choosing in every knot the most suitable option according to the decision criteria (Fig. 5). The order of defined decision criteria greatly affects the outcome of the tree. By changing the places of two sequential criteria the achieved result can be totally different. For this reason all unit processes should be handled as separate trees to decide, whether the unit process is suitable or not. Building an utmost complex tree consisting of all possible processes and ending up to a one single process is not possible or at least the result is not reliable (Quinlan, 1986; Sage and Amstrong, 2000). A group of decision trees (decision forest) would better give the potentially suitable unit processes as a result. Main issue with the decision tree is the building of the tree, i.e. the order of the decision criteria. If something has to be adjusted later on, the whole tree should be reconsidered. The information about potential processes could in some cases narrow down the number of processes significantly but in some other case the number could still remain high. Decision tree cannot also give information about the superiority of the processes. Decision forests are already used in different kinds of selection applications. One application is a software called CDMS (Clinical decision modeling dystem), which can be used to define what clinical examinations should be done and in which order to achieve the optimum result when certain resource restrictions apply (Shi and Lyons-Weiler, 2007).

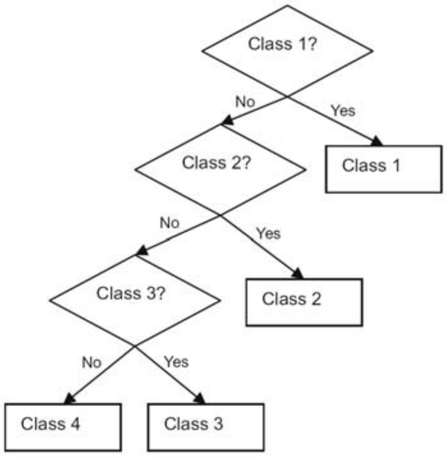

Fig. 5. A typical structure of the decision tree (Ghiassi and Bumley, 2010)

In the Multi-Criteria decision making (MCDM) the number of alternatives is first narrowed down by using certain predetermined rules. The narrowing of the alternatives reduces the need for calculation capacity. The remaining short list is then put in order using a scoring method. This can be done by very different means. TOPSIS for example is an approach where the parameters are compared with the best and worst possible values (Agrawal et al., 1991; Tong et al., 2003). The best alternative is the one closest to the optimum solution and farthest from the most undesirable solution.

Scoring of the short list seems to be a good way to compare the alternatives as long as the limits of the unit processes can be reasonably defined and there are properties that can be reliably compared using numerical scoring. The narrowing criteria have to be defined very carefully and most likely it has to be done differently for different kinds of raw materials. The same principle of narrowing down the number of alternatives based on some numerical criteria could be used with some of the other decision support methods.

The Case based reasoning (CBR) is a decision support method which uses the knowledge of past similar cases and predicts the likely outcome based on the data (Fig. 6) (Pal and Shiu, 2004; Xu, 1995). Often there is no exact match found in the previous cases so it is necessary to define, how to compare the similarity of different cases. With proper definitions, the CBR method can provide very accurate results in optimum conditions. The CBR method requires a sufficient database of similar cases than the one currently examined, otherwise the prediction is not reliable. There is no benefit in modelling analogy between generic data and unknown parameters.

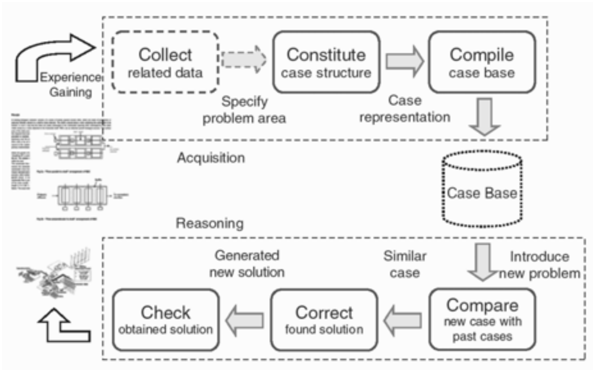

Fig. 6. The six stages of the CBR method (Avramenko and Kraslawski, 2008)

The neural network is most suitable for fairly simple optimization problems whether they are linear and nonlinear (Hassoun, 1995). It is a net consisting of an input layer, output layer and hidden layers between them (Fig. 7). The method can be used to predict for example process output with certain input if an adequate number of inputs and their outputs are known. The method can be used for example predicting the recovery with certain particle size if the recovery is known with a few other particle sizes. The level of calculating capacity demand rises rapidly with growing number of parameters affecting the situation. Positive side is that the relations between the variables do not have to be clear in order to predict the outcome (Cilek, 2002).

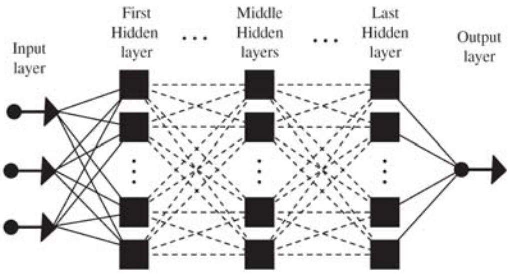

Fig. 7. Typical structure of the Neural network (Mjalli et al., 2007)

The Ant colony optimization is used to find the shortest path from “nest” to the “food”, or from the first node to the last (Dorigo and Stützle, 2004; Dorigo and Blumb, 2005). A graphic illustration of the Ant colony optimization is shown in the Fig. 8. All possible routes through the different nodes are first being tried but the shortest ones stand out. The nodes can be considered as unit processes, and then the same principle could probably be used for defining the optimum process chain. The main problem that arises is what should be the optimized parameter (or parameters), i.e. what the length of the path should represent. One alternative is to optimize a function consisting of the different variables. The variables differ however from one ore to another, so the function should be adjusted for every new ore individually and the result would be dependent on this. Different people would value different parameters differently, so the end result would most likely not be the same.

The Genetic algorithm is an efficient method used in different kinds of optimization problems. The GA alone does not however help the decision making process, instead it should be used as a part of some of the decision support methods. The GA can achieve the maximum or minimum of difficult nonlinear functions in relatively short time (Reeves and Rowe, 2002). GA can only be used to optimize a known function. It cannot find the optimum without knowing the relations of the parameters.

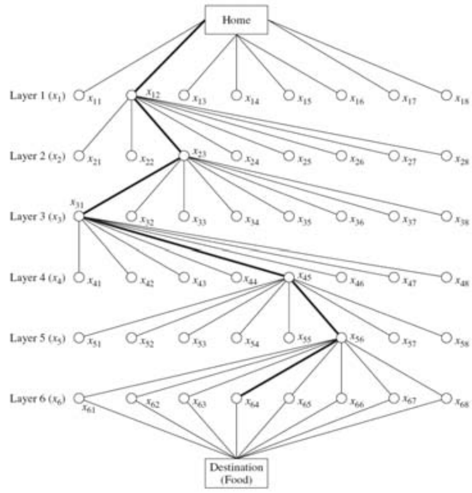

Fig. 8. A graphic illustration of the ant colony optimization (Rao, 2009)

6. DISCUSSION

A human makes judgements not only by assessing the severity of outcomes and their probability of occurrence, but also and primarily in terms of their emotional quality (Bechara et al., 2000). Because the human decisions are always based also on emotions, human brains are not objective in classifying and performing comparative analysis to factors that can be described by mathematical models. In these cases it is worthwhile to use computers to support decision making.

Each of the mentioned methods could be used in the decision making process but some methods seem to be more suitable than the others. The order of superiority depends on the viewpoint and on the data available. Different parameters act differently on different ores, so the creation of a model that would give one unquestionably best process chain is very likely impossible. Instead it would be reasonable to compare few processes or process chains that appear to be most promising based on model in a process simulator. This way the processes could be modelled detailed enough and a realistic order of superiority could be defined. The recovery of the process for example depends greatly on how optimal process conditions can be achieved. Narrowing down the alternative unit processes should be done on a reasonably high level, maybe even on category level. Comparing very similar processes without detailed modelling can result in unreliable results.

In general all the information required in decision making must be in numerical form. Therefore it can be fairly easily handled by different decision methods. It is positive that nearly all necessary information is measurable data and no subjective opinions are needed to be taken into account, except for some possible adjustable weighting coefficients. When comparing different alternatives and variables the order of magnitude also has to be taken into account. There is no point calculating for example pH and temperature on a wide range as the processes run in rather tight process envelopes.

7. CONCLUSION

The human decision making can be limited due to cognitive limitations. A person's decision making capability improves as expertise is gained, but it will take many years. Typically, the problem solving and decision making skills are reached after ten years of relevant work experience. To assist the decision making procedure different tools are available and the tools can be used, if the problem can be described in mathematical formulas or by using a set of rules.

The design phase of a hydrometallurgical process starts with analysis of the raw materials to be treated, i.e. mineralogy, chemistry, size etc. Based on this information suitable unit processes for leaching, solution purification and product recovery are designed. In this phase the traditional way has relied on design team's experience. However, for improving this first phase a decision making tool for screening of suitable process alternatives can be useful.

In this work we have studied and compared some of the known decision support and optimization methods. Based on the method descriptions the following methods are suited for development of a process selection procedure: Case based reasoning and Multi-criteria decision making.

REFERENCES

AGRAWAL, V.P., KOHLI, V., GUPTA, S., Computer aided robot selection: The multiple attribute decision making approach. International Journal of Production Research 29(1991) 8, 1629-1644.

AVRAMENKO, Y., KRASLAWSKI, A., Case based design: applications in process engineering. Springer, 2008.

BECHARA, A., DAMAISO, H., DAMAISO, A.R., Emotion, Decision Making and the Orbitofrontal Cortex. Cerebral Cortex 10(2000) 3, 295-307.

CILEK, E.C., Application of neural networks to predict locked cycle flotation test results. Minerals Engineering 15(2002), 1095-1104.
DORIGO, M., BLUMB, C., Ant colony optimization theory: A survey. Theoretical Computer Science 344(2005), 243 – 278.
DORIGO, M., STÜTZLE, T., Ant Colony Optimization. MIT Press, 2004, 320.
GHIASSI, M., BURNLEY, C., Measuring effectiveness of a dynamic artificial network algorithm for classification problems. Expert Systems with Applications 37(2010), 3118-3128.
HASSOUN, M.H., Fundamentals of Artificial Neural Networks. Massachusetts Institute of Technology, 1995.
HAYES, P., Process Selection in Extractive Metallurgy. Hayes Publishing Co, Brisbane, 1985, 406.
OYJ, O., 2010, Sim – Process Simulation. www.outotec.com/pages/Page.aspx?id=35374 &epslanguage =EN. Viitattu
MJALLI, F.S., L-ASHEH, S., ALFADALA, H.E., Use of artificial neural network black-box modeling for the prediction of wastewater treatment plants performance. Journal of Environmental Management 83(2007) 329-338.
PAL, S., SHIU, S., Foundations of Soft Case-Based Reasoning. John Wiley & Sons, 2004,. 298.
QUINLAN, J.R., Induction of Decision Trees. Machine Learning 1(1986), 81-106.
RAO, S.S., Engineering Optimization - Theory and Practice. John Wiley & Sons, 2009.
REEVES, C.R., ROWE, J.E., Genetic Algorithms - Principles and Perspectives : A Guide to GA Theory. Kluwer Academic Publishers 2002,. 345.
SAGE, A.P., ARMSTRONG, J. E. Jr., Introduction: Types of Decisions. In: Introduction to Systems Engineering. John Wiley & Sons, 2000,. 547.
SHI, H., Lyons-Weiler, J., Clinical decision modeling system. BMC Medical Informatics and Decision Making 7(2007) 23, 17.
TONG, K.W., KWONG, C.K., IP, K.W., Optimization of process conditions for the transfer molding of electronic packages. Journal of Materials Processing Technology 138(2003), 361-365.
WADSWORTH, M., Leaching - Metals Applications. In: Handbook of Separation Process Technology, ed. Rousseau, R. John Wiley & Sons, New York, 1987, 500-539.
XU, L.D., Case based reasoning. Potentials, IEEE 13(1995) 5, 10-13.

Rintala, L., Lillkung, K., Aromaa, J., *Zastosowanie naukowych metod podejmowania decyzji oraz optymalizacji do wyboru alternatywnych jednostkowych procesów hydrometalurgicznych*, Physicochem. Probl. Miner. Process., 46 (2011) 229-242, (w jęz. ang), http://www.minproc.pwr.wroc.pl/journal

Rozwój linii technologicznej w hydrometalurgii opiera się zwykle na doświadczeniu i preferencjach personelu. Doświadczenie i nabyta wiedza w tej dziedzinie są bardzo trudne do przekazania. Dlatego też podjęto próbę opracowania metody wspomagania procesu podejmowania decyzji i wyboru przy planowaniu linii technologicznych. Najważniejszym elementem procesu decyzyjnego jest opis problemu. Ta część procesu dyskutowana jest w oparciu o metody wspomagania procesu decyzyjnego. Dodatkowo przedyskutowano przebieg procesu decyzyjnego w przypadku typowych dla hydrometalurgii linii technologicznych. Praca ta zogniskowana jest na zagadnieniu znalezienia odpowiednich narzędzi, które mogłyby pomóc w zgrubnym wyborze pomiędzy różnymi procesami jednostkowymi. Optymizacja technologii byłaby następnym krokiem jej rozwoju, ale problem ten nie jest w pracy dyskutowany.

słowa kluczowe: procesy hydrometalurgiczne, metody decyzji i optymalizacji, podejmowanie decyzji