ICOTA '98

OPTIMIZATION

TECHNIQUES AND APPLICATIONS

VOLUME 2

Edited by

L. Caccetta[1], K.L. Teo[1], P.F. Siew[1], Y.H. Leung[2], L.S. Jennings[3], V. Rehbock[1]

[1] *School of Mathematics and Statistics*
Curtin University of Technology, Australia

[2] *Australian Telecommunications Research Institute*
Curtin University of Technology, Australia

[3] *Department of Mathematics*
The University of Western Australia

PROCESS SYSTEMS ENGINEERING AND MINERAL INDUSTRIES: FLEXIBILITY ANALYSIS IN A FLOTATION CIRCUIT

Parisa A. Bahri[1], Tran Ngo[2]

1. School of Engineering, Murdoch University, Murdoch, WA 6150
Email: parisa@eng.murdoch.edu.au
2. Chemical Engineering Department, Sydney University, NSW 2006

ABSTRACT

The goal of a process design is to produce a plant that is optimal with respect to cost and performance. A good design should also exhibit operability characteristics that allow economic performance to be realisable in a practical operating environment. The aim of this research is to establish an investigation of operability, especially flexibility, of a flotation plant. Several flotation circuits have been considered for this study, which are different in structure. A superstructure that contains all these alternatives is built and an MINLP program is setup. Using GAMS optimisation package with DICOPT as the solver, the best flowsheet that maximises the recovery of the valuable mineral is found. The next step involves the flexibility analysis of the best four flowsheets using a systematic algorithm. It is found that the most flexible plant is not necessarily the flowsheet found in the synthesis stage, confirming the fact that by including such flexibility at the design phase one can often avoid costly changes needed later to reduce product variability.

INTRODUCTION

Australia's mining and processing industries are very significant contributors to our export income. These industries add value to our natural resources, and yet there is still considerable scope for economic improvement. Benefits in the range of 2% to 6% of operating costs are to be gained through the use of better design and operational methods – process systems engineering techniques – to leverage the quantity and quality of the products. On a national scale, this represents a benefit of some \$250 - \$1000 million per annum of revenue for the process industries.

During the past decade product quality and its relationship to customer demand has increasingly become important. It is no longer sufficient to focus only on plant designs that maximise material yield and minimise utility usage. The recent focus on product variability has intensified the need to design processes that have good operability characteristics, are easy to operate, and result in low product variability (Downs and Ogunnaike, [1]). Current industrial practice to arrive at plant designs that include operability and variability notions is described from several viewpoints. These include (1) a political/cultural viewpoint, (2) recurring technical issues, (3) tools and techniques in use, and (4) future needs. There are many issues that are in need of work and innovation to achieve plant designs that weave in operability considerations. Those manufacturers building plants that can provide products with low variability will continue to capture an increasing share of the market and will be the preferred suppliers.

As stated by Nishida et al. [2], "process synthesis is an act of determining the optimal interconnection of processing units as well as the optimal type and design of the units within a process system. The task is then to select a particular system out of the large number of alternatives which meet the specified performance". This specific performance could be either an economic objective or something related to the operability of the plant.

Currently many methods are used to include the operability perspective into process design. But bridging the gap between academia and industry especially in the mineral industry is an urgent need. In this paper the technical ingenuity required to achieve the optimal performance of the plant combined with the practical savvy that makes a plant pleasant to operate, is presented. The approach used in here consists of process modelling, generation and optimisation of alternatives, and operability analysis that has been applied to a flotation circuit.

What is Operability?

A designed plant must be able to cope with various uncertainties. This means that a plant has to maintain the feasibility as well as the optimality of the operation at all times. This will lead us to the concept of flexibility that is one of the major aspects of operability analysis. In most of the methodologies developed for flexibility analysis, a multi objective optimisation problem is formulated in which both the performance objective as well as the feasibility objective are pursued. Mathematically, a steady state flexibility problem can be presented as follows (Bahri, [3]):

$$\begin{aligned}
&\min_{z,d,y}\ \Phi\left(z,d,y,x,\theta^{N},p_{p}\right) \qquad\qquad (1)\\
&\text{s.t.}\\
&h_{i}\left(z,d,y,x,\theta^{K},p_{p}\right)=0 \qquad i\in E\\
&\max_{\theta\in\Gamma}\ \max_{j}\ g_{j}\left(z,d,y,x,\theta^{K},p_{p}\right)\leq 0 \qquad j\in I\\
&z\in Z\\
&d\in D\\
&y\in\{0,1\}\\
&\theta^{k}\in\Gamma
\end{aligned}$$

Where z is the vector of decision variables, d is the vector of design variables, x is the vector of state variables, θ is the vector of disturbances or uncertainties, and p_p is the vector of system's parameters. h_i and g_j are the sets of equality (model equations) and inequality (operational) constraints, respectively. Integer variables y are used to define the best flowsheet, and K is a counter that defines the number of the iteration.

To solve the above multiobjective optimisation problem a simple iterative decomposition algorithm could be used (Bahri, [3]). In this approach the problem is decomposed into two levels at each iteration: (1) Outer level in which the main optimisation problem with objective Φ is solved (for a given set of disturbances θ), and (2) Inner level in which for the optimal set of conditions found in outer level, the maximum deviation of inequality constraints, g_j will be calculated. The algorithm iterates until an optimal set of operating conditions or design variables are found that satisfy all the inequality constraints (feasibility is ensured). The schematic of this algorithm is shown in Fig 1. It can be noticed that the optimisation problem in outer level of this algorithm would be an MINLP problem and for inner level it will be an NLP, as the flowsheet will be set (y = y* found in outer level).

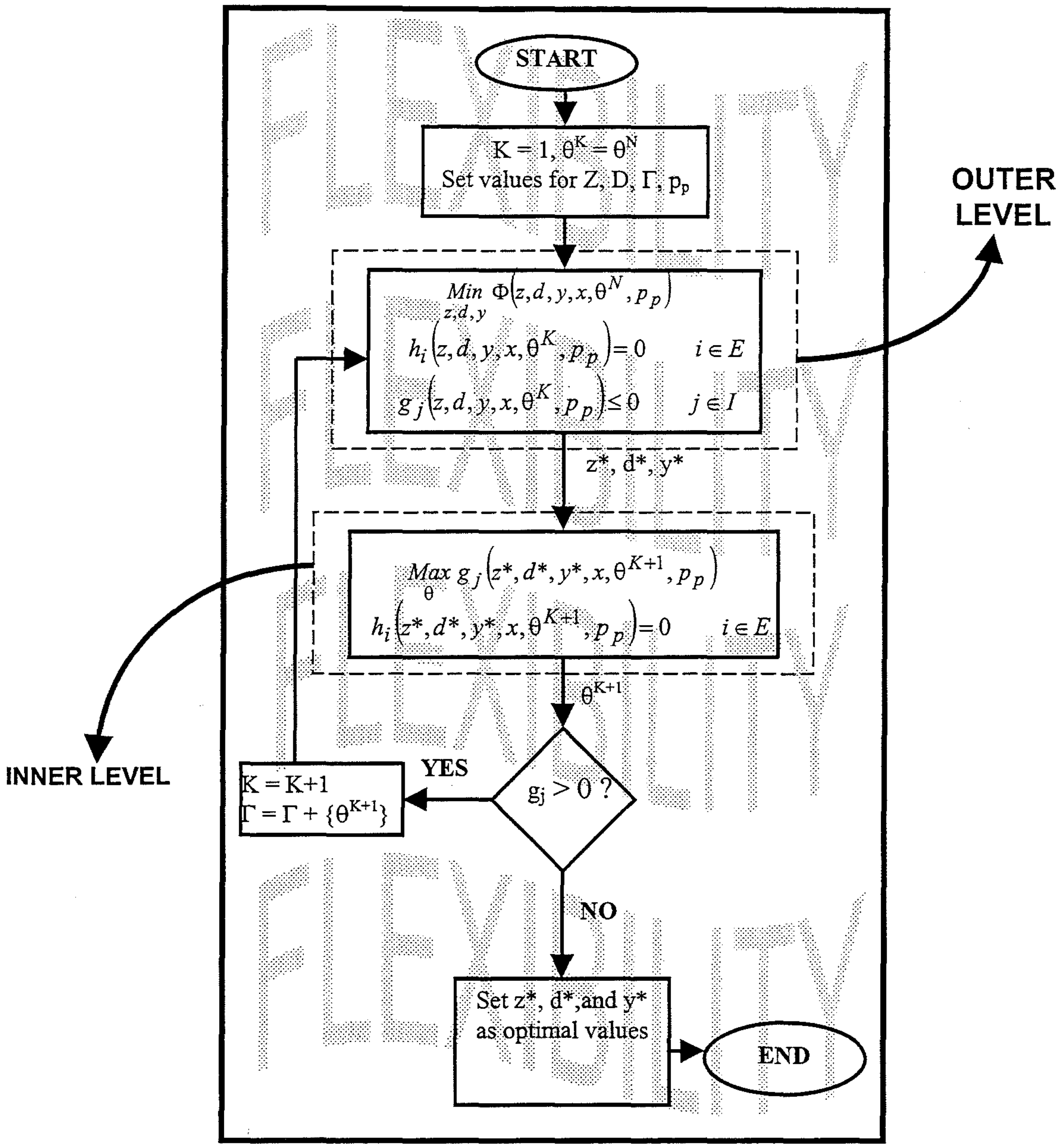


Fig. 1 Schematic of the procedure for flexibility analysis

Case Study: Flotation Circuit

Flotation is one of the methodologies used for the separation of minerals from ore. Without the development of froth flotation there would be no mining industry as today, since the entire world's supply of copper, lead, zinc and silver is first collected in the froth of the flotation process. Due to this fact and in order to practice the operability analysis in a mineral process, a flotation circuit has been used (Chan et al., [4]) as the case study. The circuit consists of three flotation cells that can be arranged in 11 different ways. The objective function used for this system was to maximise the recovery of the valuable mineral in the final product, by manipulating the volume of the cells. The operational constraints are defined as follows:

1. The total volume of the cells should be less than 50 m^3.
2. The grade of the final product should not be less than 60% (market constraint).
3. The recovery of the product should be greater than 87% (economic constraint).

The disturbances to the system are the feed flow rate and feed grade, which vary in the following ranges:

$$0.095 \leq \text{Feed grade} \leq 0.15 \text{ (nominal value} = 0.12)$$
$$95 \leq \text{Feed flow rate} \leq 150 \text{ (nominal value} = 120)$$

The first step in the operability analysis of this system was to find the optimal plant without considering the effect of disturbances (nominal optimum). To do this, a superstructure containing all flowsheets was designed (Grossmann, [5]), as shown in Fig. 2. It should be noted that some of the shaded squares or white ovals are added to the flowsheet as mixers and splitters, in order to create the superstructure.

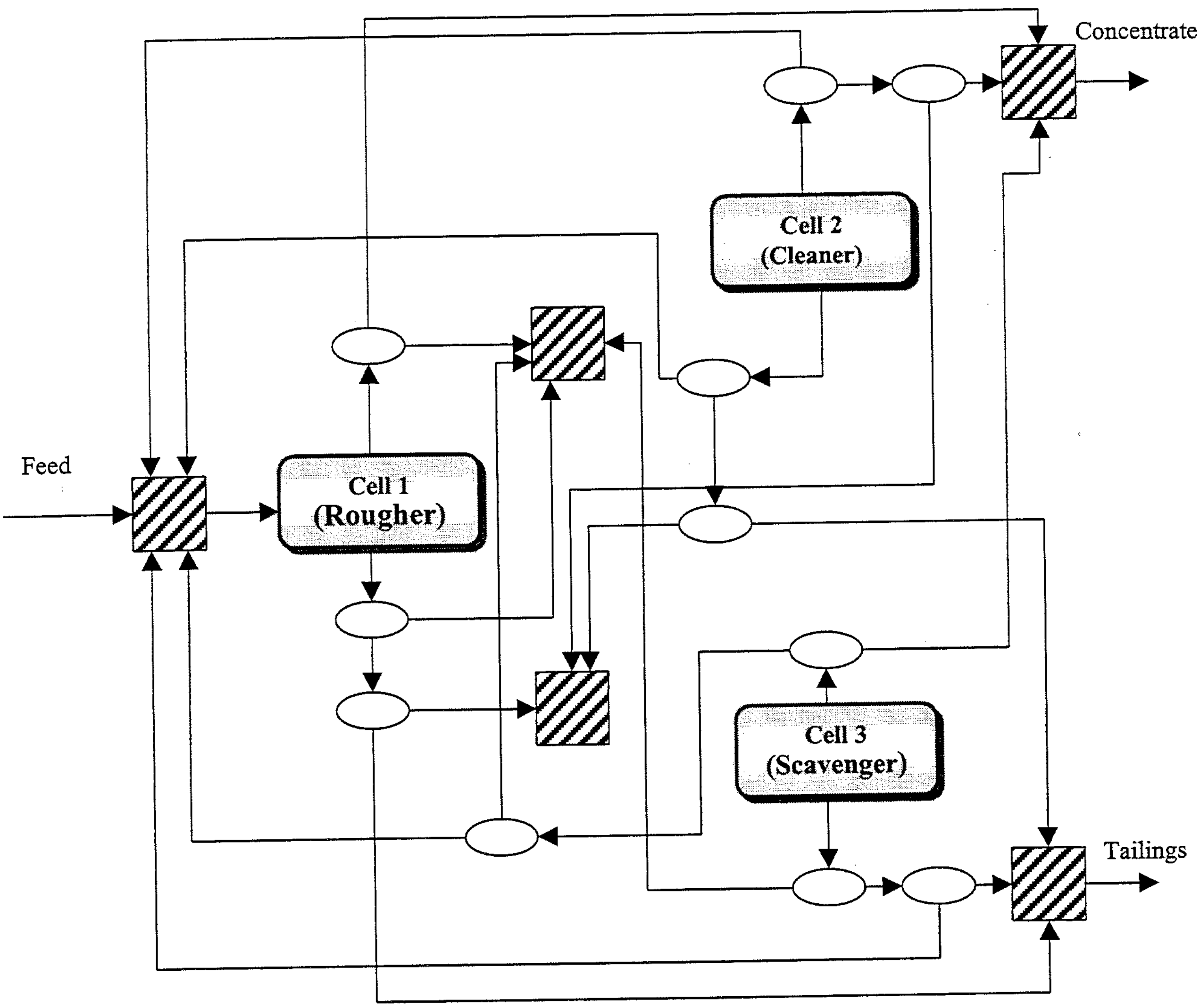
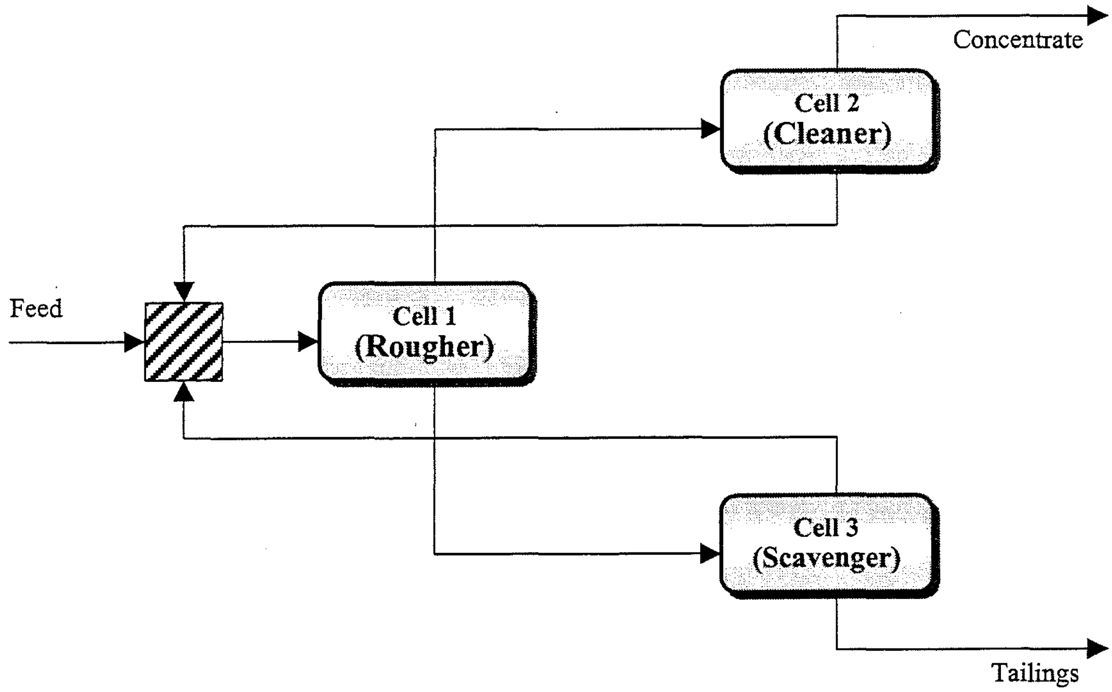


Fig. 2 Super structure for the flotation circuit

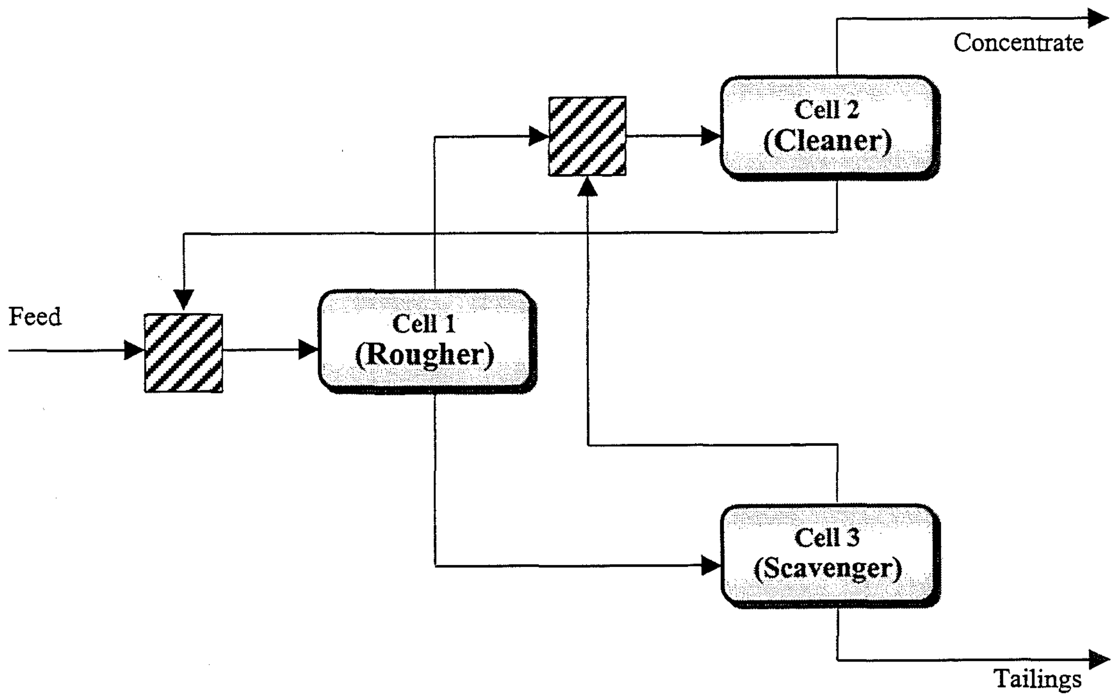
To solve the resulting MINLP problem, the software package GAMS™ (Brooke et al., [6]) with solver DICOPT has been used. The result from the program has shown that the best flowsheet (flowsheet 2 in Fig. 3) had a recovery of about 94.45, the product grade of about 60% and total cell volumes of about 50 m^3.

The next step was to study the flexibility of the plant found in the previous step. As the basis of comparison, four of the flowsheets with highest recoveries was selected (Fig. 3). The algorithm in Fig. 1 was then used in order to find the best operating conditions for each flowsheet so that the feasibility of the operation in the face of disturbances could be guaranteed.

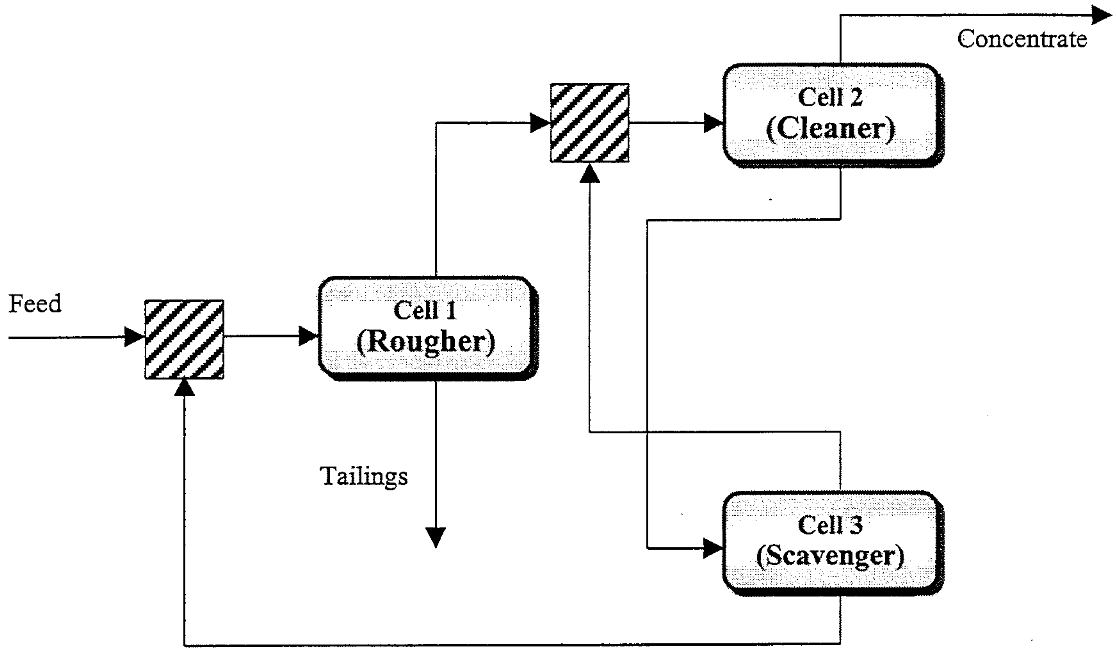
Flowsheet 1



Flowsheet 2



Flowsheet 3



Flowsheet 4

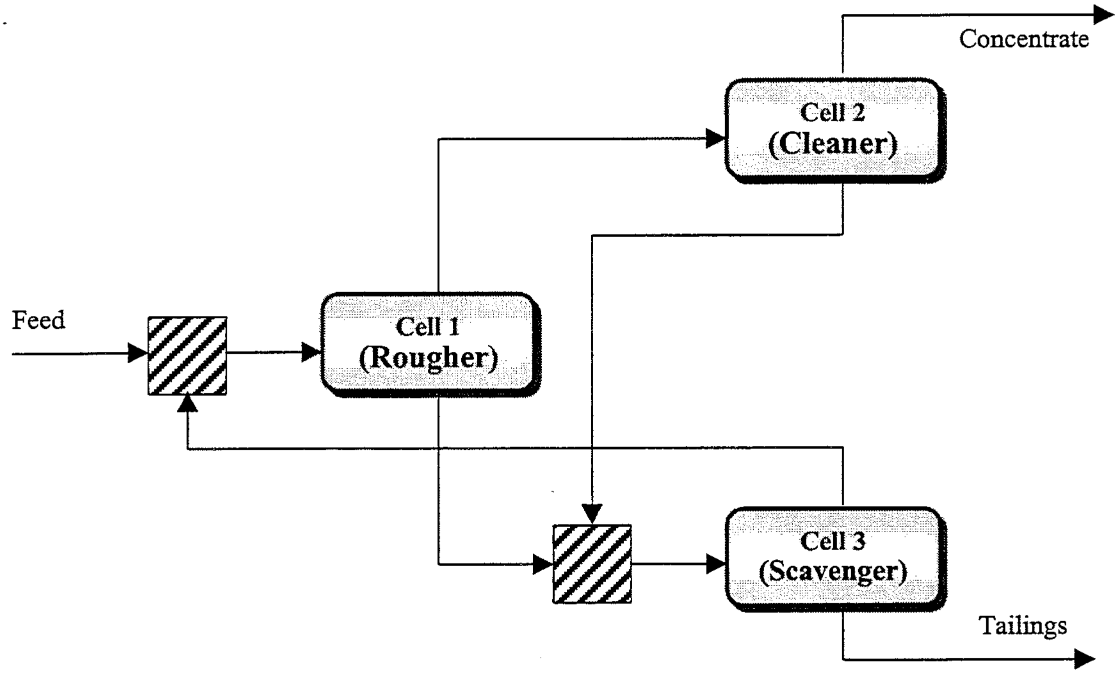


Fig. 3 The flowsheets used for flexibility analysis

In order to analyse the flexibility, the outer levels and the inner levels of the algorithm were set up in GAMS. The outer levels produce MINLP problems that are solved with DICOPT solver and the inner levels are NLP problems, solved by MINOS. For all four flowsheets, the algorithm converged in 2 iterations, with the recovery and/or grade constraints violated in the inner level subproblems of the first iteration. The outer level of the second iteration gave the best flowsheet and volumes of the cells that cope with uncertainties and give the highest recovery of all. The results from the optimisation of these flowsheets at nominal conditions and also from the second iteration of the flexibility algorithm for the selected flowsheets are shown in Tables 1and 2, respectively.

Table 1. The nominal optimisation results for the best four flowsheets

Flowsheet	Rougher volume	Scavenger volume	Cleaner volume	Product Grade	Recovery
1	24.560	16.797	8.643	60.0	94.228
2	23.796	17.540	8.664	60.0	94.449
3	38.304	3.650	8.046	60.0	87.71
4	23.401	18.071	8.528	60.0	92.967

Table 2. The results from the second iteration of flexibility algorithm for the best four flowsheets

Flowsheet	Rougher volume	Scavenger volume	Cleaner volume	Product Grade	Recovery
1	25.034	19.579	5.387	71.692	93.626
2	25.265	19.351	5.383	71.651	93.396
3	39.968	5.028	5.005	71.582	86.581 (Not Feasible)
4	16.291	28.432	5.277	71.559	91.198

As can be seen from the results, flowsheet 2 that was synthesized as the best flowsheet for the nominal values of disturbances, did not perform that good in the flexibility step. Flowsheet 1 has the highest recovery in the presence of disturbances due to its arrangement of different units, and therefore would be selected as the best design with the least product variability. It should also be noted that flowsheet 3 becomes infeasible in the presence of disturbances and there would be no combination of the cell volumes to make the recovery higher than 87%.

CONCLUSION

In this paper a simple and efficient algorithm has been used for the operability analysis of a mineral plant. The flexibility of the operation of a flotation circuit has been studied in the design and synthesis stage and it has been found that:

1. A plant that has been designed by simple optimisation can not operate feasibly in the presence of disturbances, as some of the operational constraints would be violated.
2. By changing the operational or design conditions of this plant it may be possible to maintain the feasibility of operation but not the optimality.
3. Using the algorithm for flexibility analysis the best optimal and flexible plant could be synthesied that is not necessarily the one found at the nominal optimisation step.

It should be mentioned that this study is the first step in the operability assessment of a mineral plant. Obviously the implementation of a control system would significantly change the results and allow the plant to operate closer to its original optimum. The same algorithm can be used in a dynamic environment where controllers are present, and the optimal design as well as the optimal control configuration and parameters can be found.

REFERENCES

[1] Downs, J. J., and B. Ogunnaike, "Design for Control and Operability: An Industrial Perspective", *AICHE Symposium Series*, **91**, 115 - 123, (1995).
[2] Nishida, N., G. Stephanopoulos and A. W. Westerberg, "A Review of Process Synthesis", *AICHE Journal*, **27**, 321 – 351, (1981).
[3] Bahri, P. A., *An Integrated Procedure for Operability Analysis of Chemical Plants*, PH.D thesis, University of Sydney, Sydney, Australia, (1995).
[4] Chan, W. K., G. W. Barton, and J. D. Perkins, "Interaction Between Process Design and Process Control: The Role of Open-Loop Indicators", *Journal of Process Control*, **1**, 161 – 170, (1991).
[5] Grossmann, I. E., "MINLP Optimisation Strategies and Algorithms for Process Synthesis", *Technical Report EDRC*, Dept. of Chem. Eng., Carnegie Mellon University, Pittsburg, (1990).
[6] Brooke, A., D. Kendrick, and A. Meeraus, *GAMS 2.25 User's Guide*, Scientific Press, (1992).