Mineral Process Design for Sustainability

Luis A. Cisternas
CICITEM - Research Center for Mining
and
Department of Chemical Engineering
Universidad de Antofagasta
Antofagasta - Chile

PASI 2011

Outline

- Motivation
- PSE at CICITEM
- Models for Design
- Methods for Process Synthesis

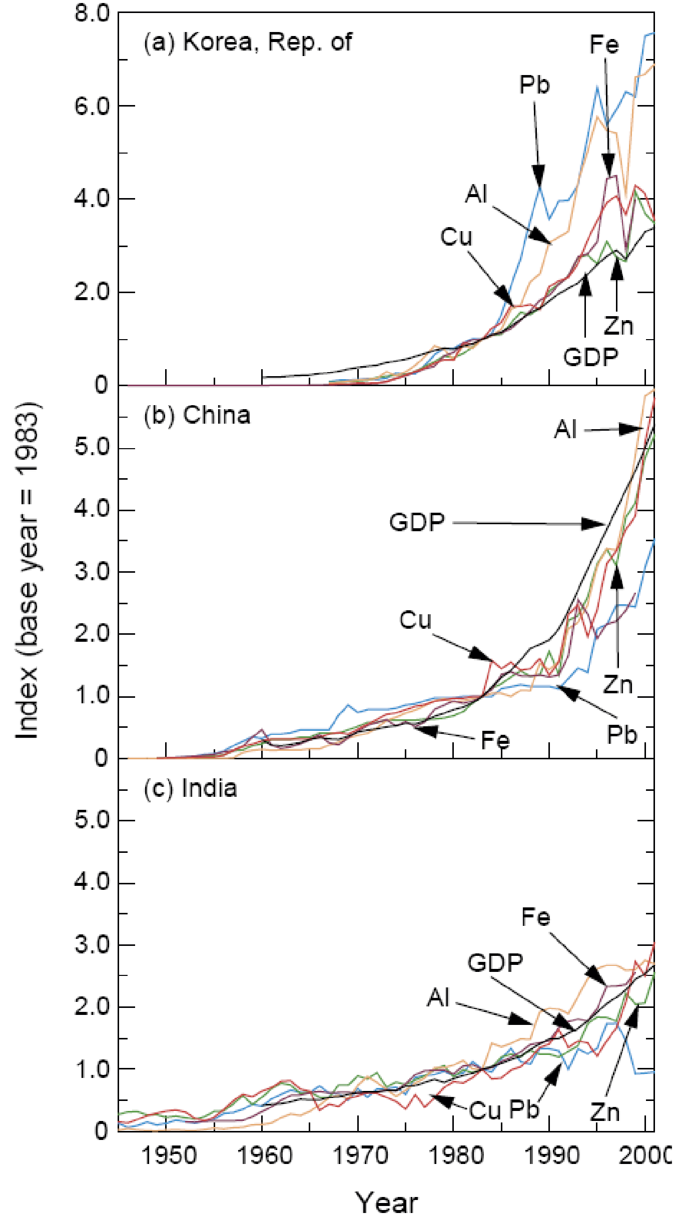
Motivation

- The minerals industry is looking for progress in the reduction of the impacts of its mining and mineral processing operations.
- They have several challenges for sustainable mineral operation with lower environmental and social impact, but keeping profitable operations.
- These challenges must be addressed in the design, operation and post-closure phases, but the design phase give us the biggest opportunity for reducing the impact of operations and increasing profit (McLellan et al. 2009).

Mc Lellan B.C., Corder G:D:, Giurco D., Green S., 2009, Incorporating sustainable development in the design of mineral processing operations – review and analysis of current approaches, Journal of Cleaner Production, 17(16), 1414-1425.

Balance between global consumption and the available production

With continuing rapid economic growth and industrial expansion, high population growth and urbanization, both key metals consumption and GDP are expected to grow in Asia. Asia will have a strong impact on the global trends in key metals consumption

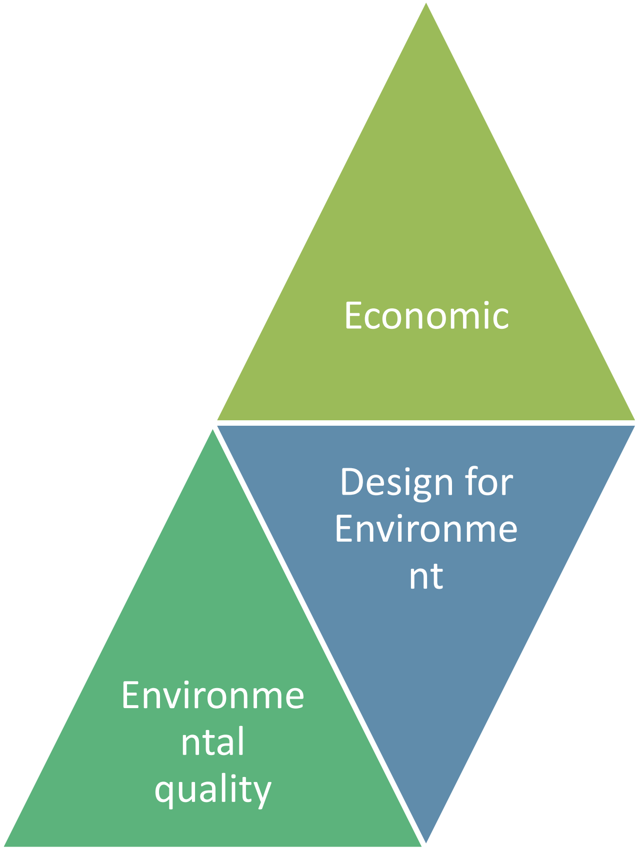


Takashi Nishiyama, The roles of Asia and Chile in the world copper market, Resources Policy 30 (2005) 131–139

Design for Sustainability (DfS)

- Several design tools are available that incorporate sustainability elements, but usually these had not been applied to mineral process
- The principal social factors considered are health and safety and the reduction in emissions of toxic waste products.

Design for Environment (DfE)



- The emphasis on reducing the environmental impact, both in per tonne of product and on total amount of emissions and reduction.

Challenges in Metal and Mineral Industry*

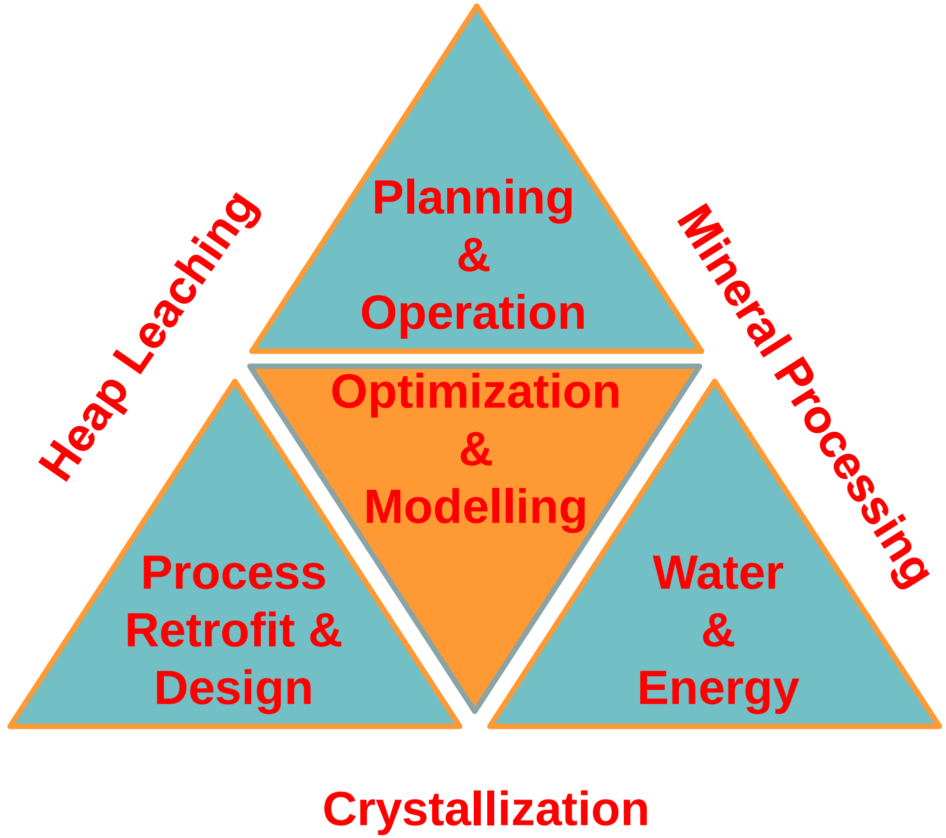
- Limited availability of thermodynamic information covering the full spectrum of chemical conversions embodied in minerals technologies.
- Low grade of mineral ores (and as a result, the myriad of impurities which must be removed typically).
- The variability and non-homogeneity of ores resulting in significant variation between ore bodies, as well as over the life of a single mine.

* Stewart M, Basson L, Petrie JG., 2003, Evolutionary design for environment in minerals processing. Process Saf Environ Prot,81:341–51

Challenges in Metal and Mineral Industry

- The large energy demand for physical transformation.
- The significant role of poorly understood particulate processes in beneficiation and refining.
- The relative conservation of the industry for technological change, itself captured in the dominance of vendor-driven design solution.
- The environmental impacts of minerals processing.

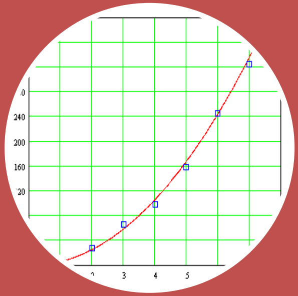
Core Research Activities



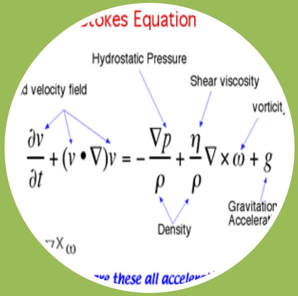
Core Research Activities

	Models		Optimization			Post Activities
	First Principles	Empirical	Process Design & Retrofit	Planning & Operation	Water & Energy	
Heap Leaching						
Crystallization						
Mineral Processing						

Models for Design



Empirical Models (based in to adjust a curve to experimental data)

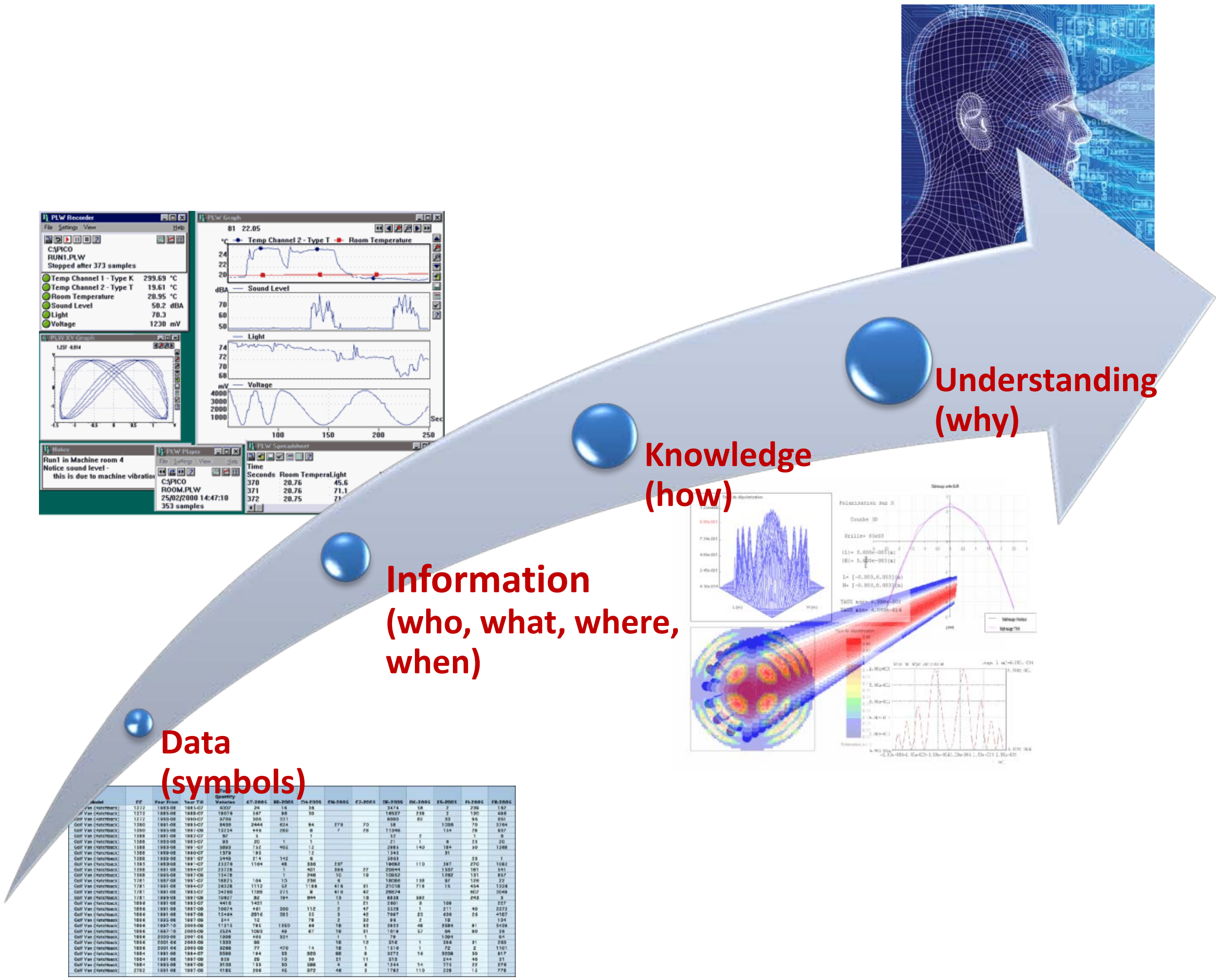


Phenomenological Models (Based in the physics equations which describe the system)

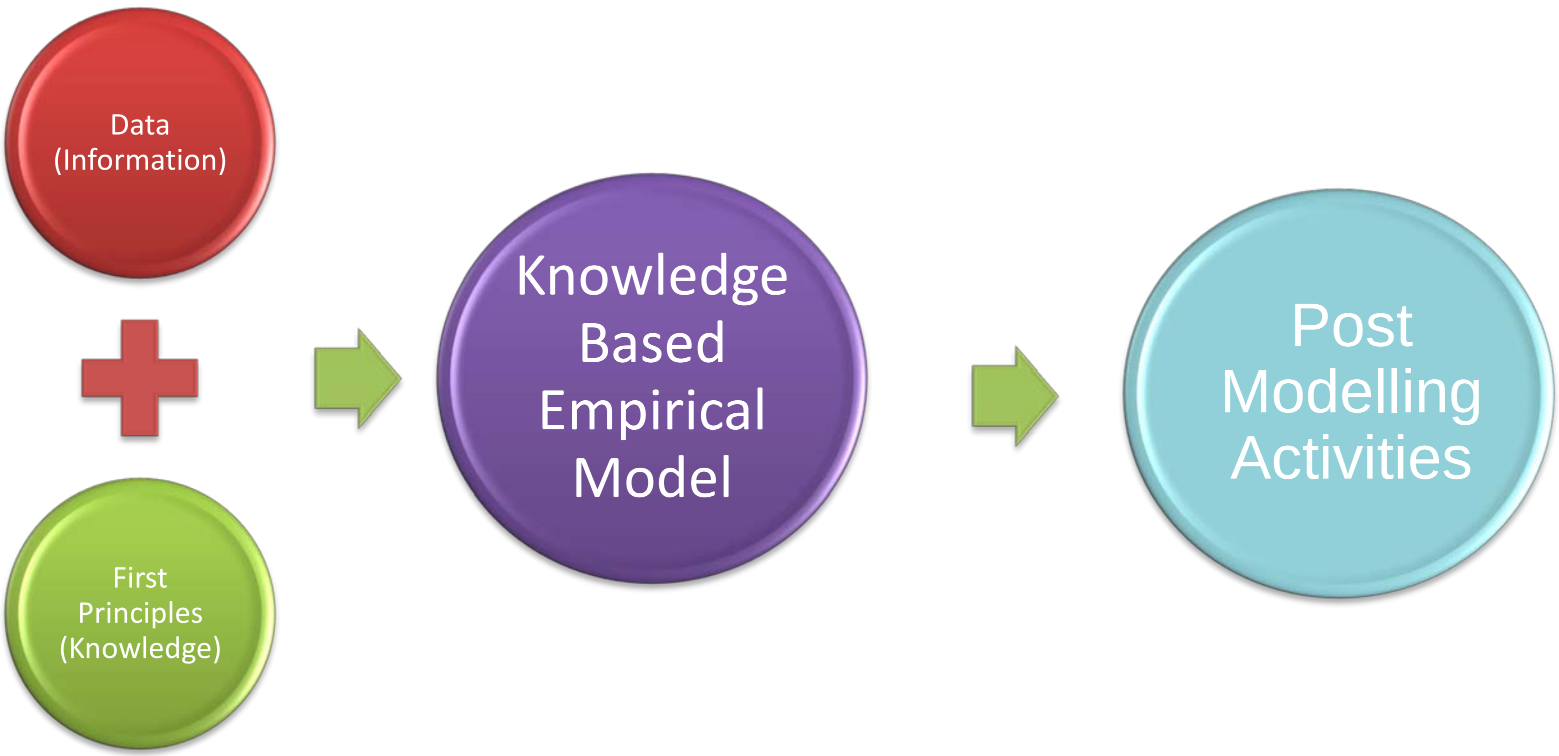
$$R_\theta = R_\theta^\infty \left(1 - e^{-k_\theta\left(\frac{u_S}{\varepsilon_b Z}t - \omega\right)}\right),$$

Hybrid Models (Based in the combination of the two latter approaches)

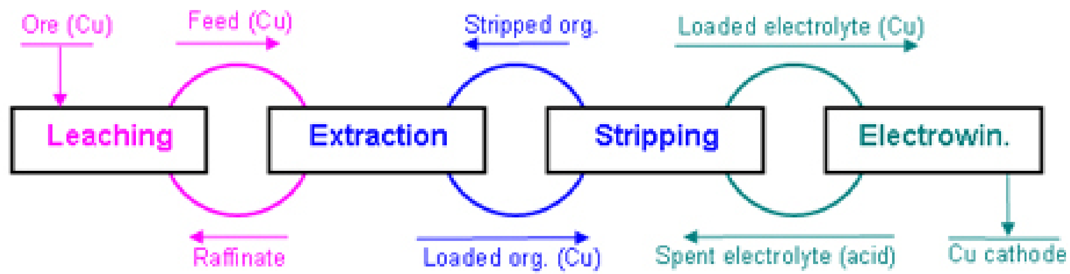
Knowledge Map

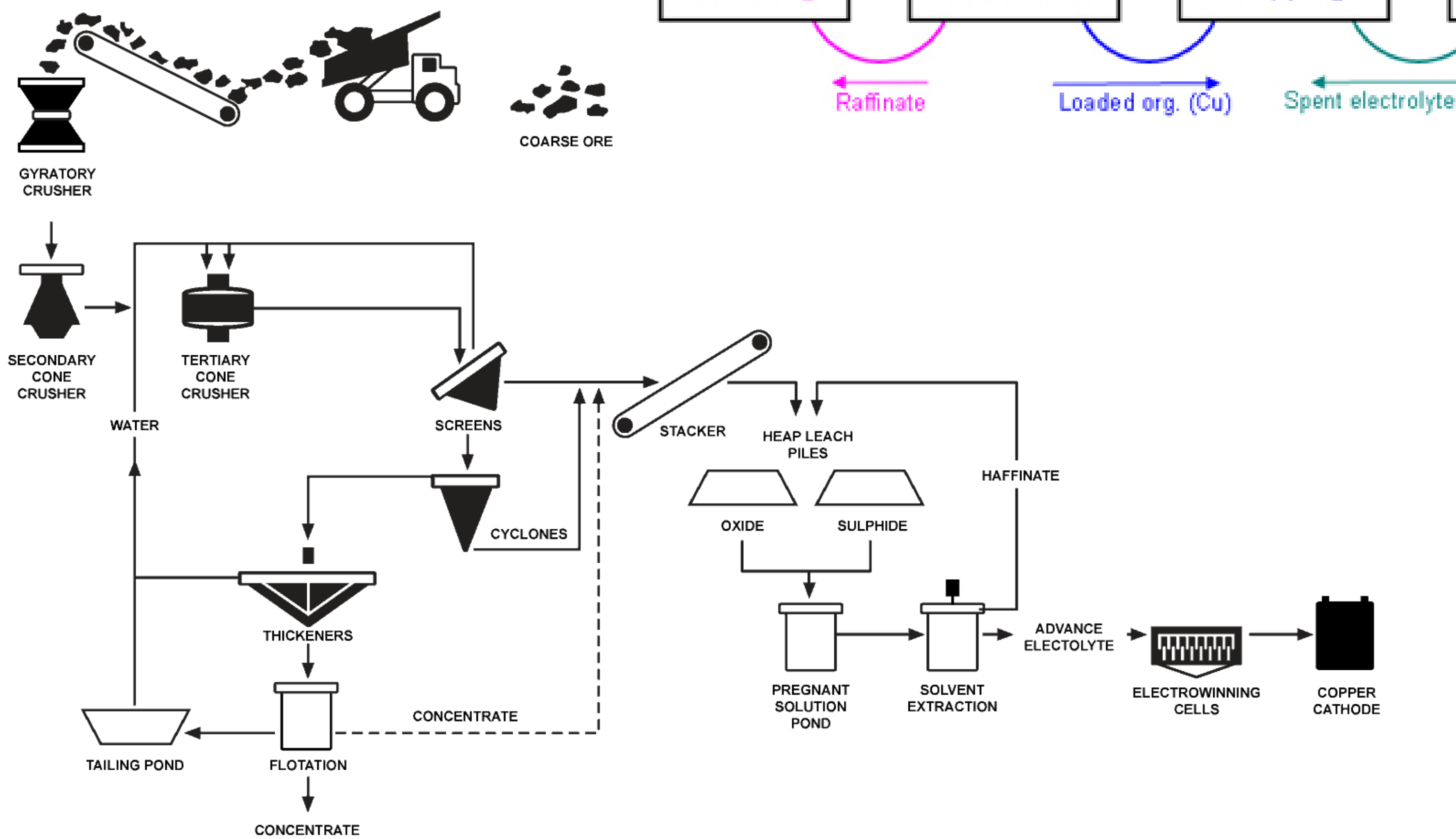


Knowledge Based Empirical Model

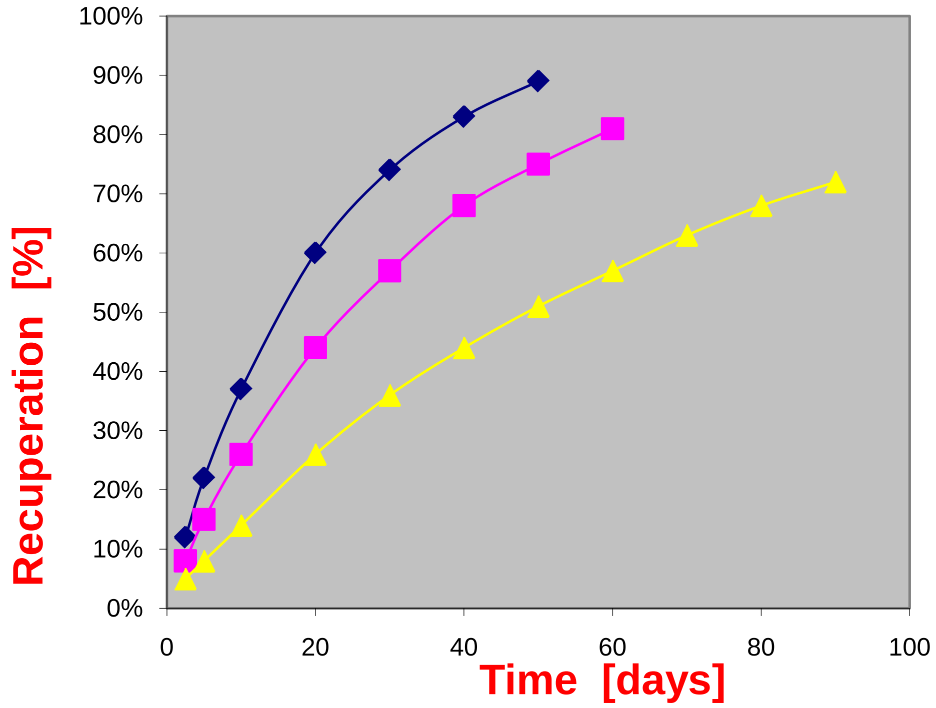


Heap Leaching





Data & Information



order kinetic

$$\frac{dy}{dt} = -k_t \quad y^{n_t} \quad ,$$

constant kinetic

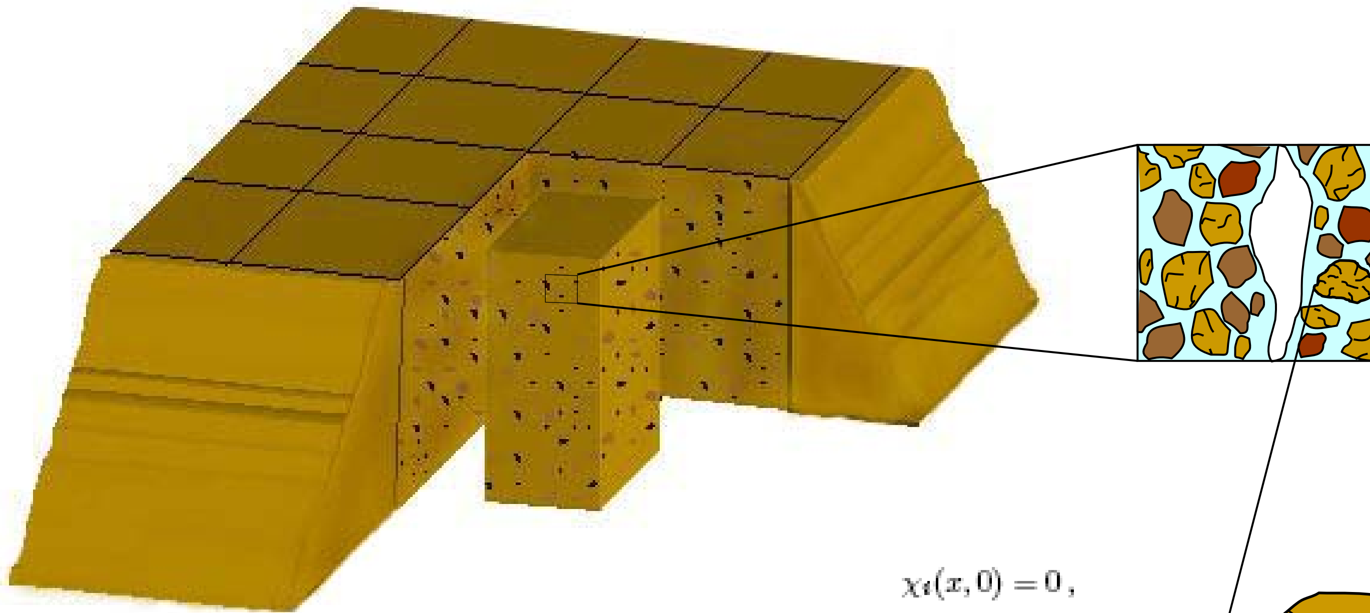
$$y = R_t^{\infty} - R_t$$

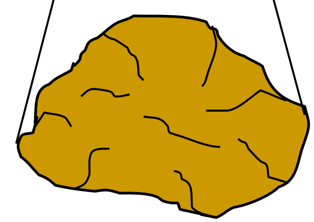
$$R_t(\omega) = 0$$

delay

Motivation | PSE at CICITEM | Models for Design | Methods for Process Synthesis

Knowledge: Dixon and Hendrix Model





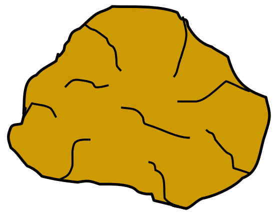
$$\chi_t(x,0) = 0\,,$$

$$\chi_t(1,t) = \chi_b\,,$$

$$\frac{\partial \chi_t}{\partial x}(0,t) = 0\,.$$

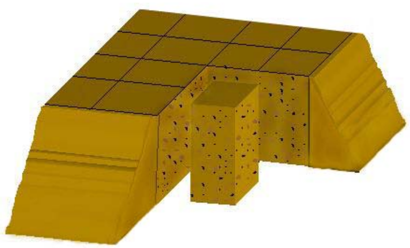
$$\frac{3}{\nu\omega}\frac{\partial \chi_t}{\partial \theta} = \frac{\partial \chi_t}{\partial t} = \frac{\partial^2 \chi_t}{\partial x^2} + \frac{2}{x}\frac{\partial \chi_t}{\partial x} + k_p\sigma_p\alpha\,,$$

Knowledge



$$\tau = \frac{D_{Ae} t}{\varepsilon_o R^2}$$

particle level



$$\theta = \frac{u_s t}{\varepsilon_b Z}$$

heap level

$$E(\theta) = \beta v \int_0^{\theta} \chi_{ib}(1, t) dt$$

$$\bar{\omega} = \frac{D_{Ae}}{r^2 \varepsilon_0} \frac{\varepsilon_b Z}{u_s} \omega$$

. delay

Knowledge Based Empirical Model

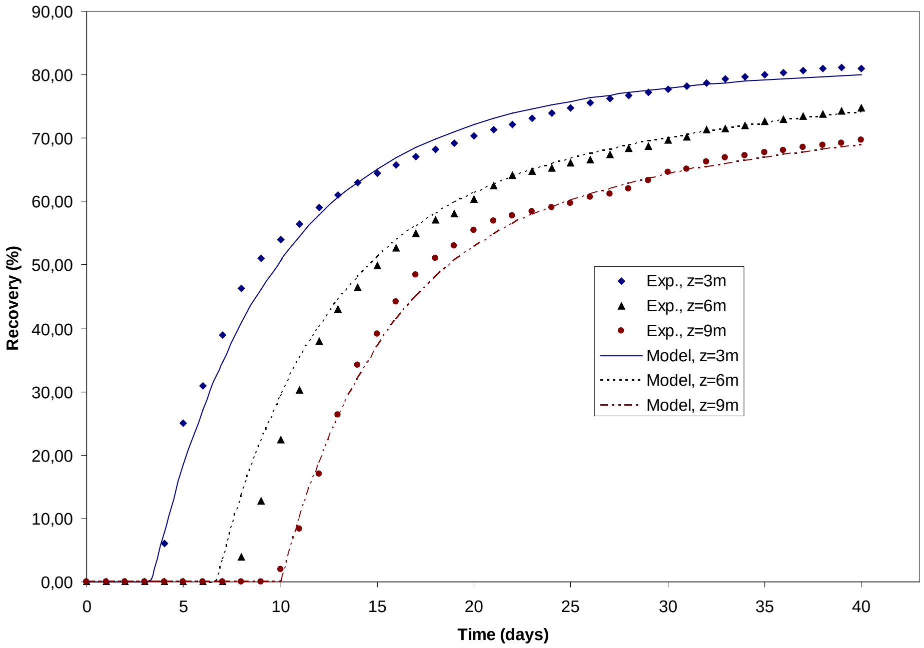
$$R_\tau = R_\tau^\infty \left(1 - e^{-k_\tau\left(\frac{D_{Ae}}{r^2\varepsilon_0}t - \varpi\right)}\right);$$

$$R_\theta = R_\theta^\infty \left(1 - e^{-k_\theta\left(\frac{u_s}{\varepsilon_b Z}t - \omega\right)}\right),$$

$$R = R_\theta + R_\tau.$$

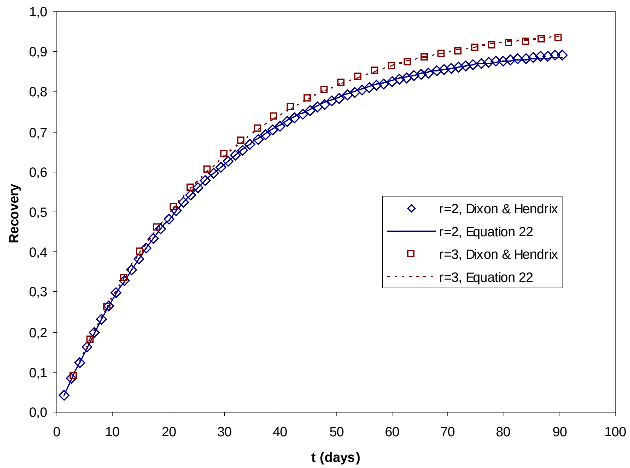
$$R = R^\infty \left[1 - \alpha\, e^{-k_\theta \frac{u_s}{\varepsilon_b Z}(t - \frac{\varepsilon_b Z}{u_s}\omega)} - (1-\alpha)\; e^{-k_\tau \frac{D_{Ae}}{r^2 \varepsilon_0}(t - \frac{\varepsilon_b Z}{u_s}\omega)} \right] .$$

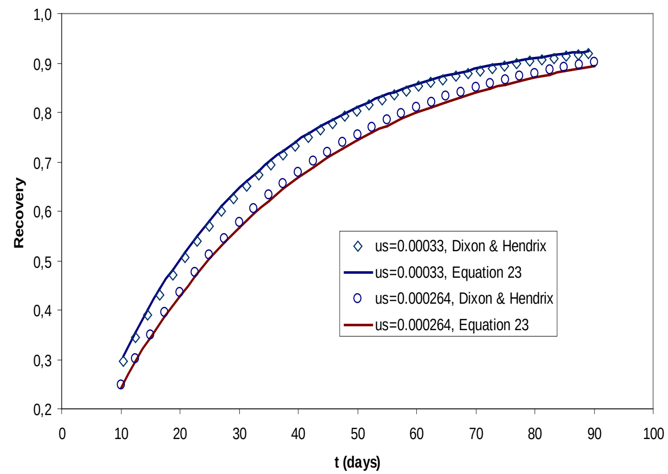
Results versus Data

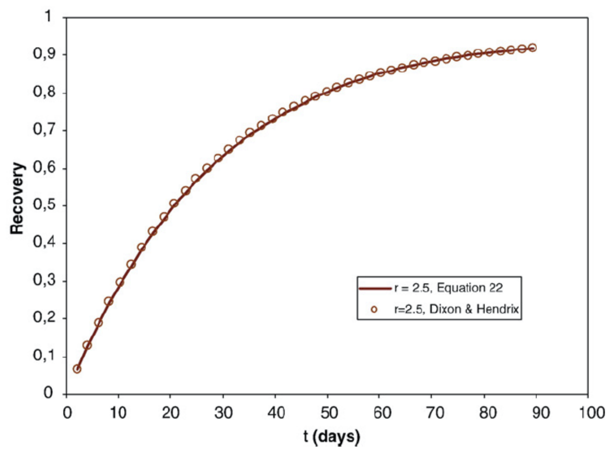


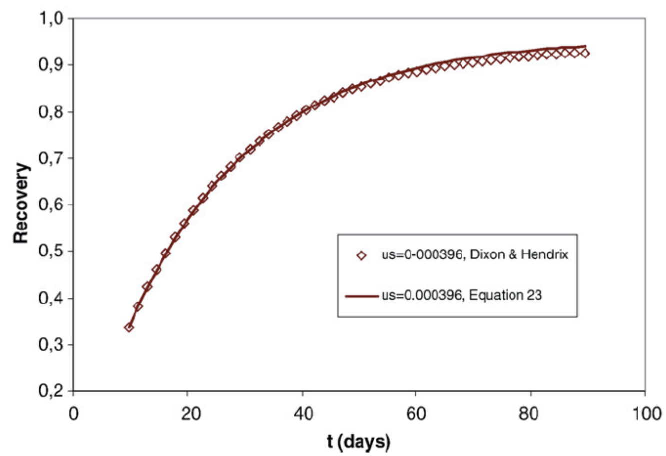
Leaching tests with copper minerals from northern Chile in heaps measuring 3, 6 and 9 m in height

Results versus Dixon & Hendrix



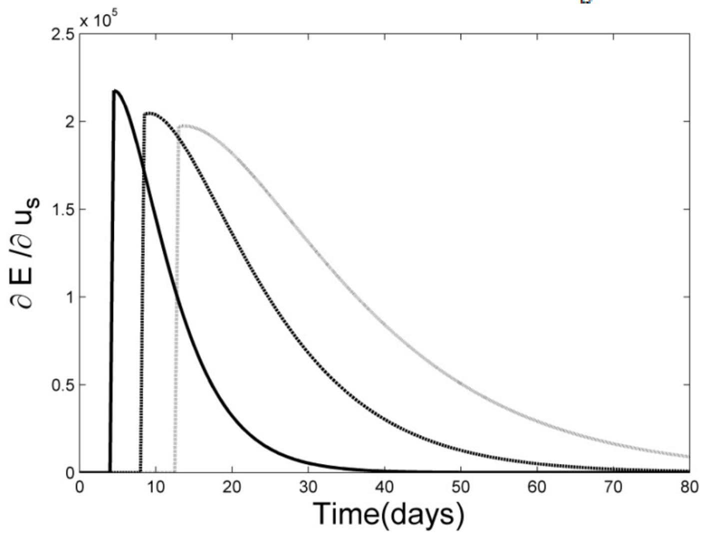


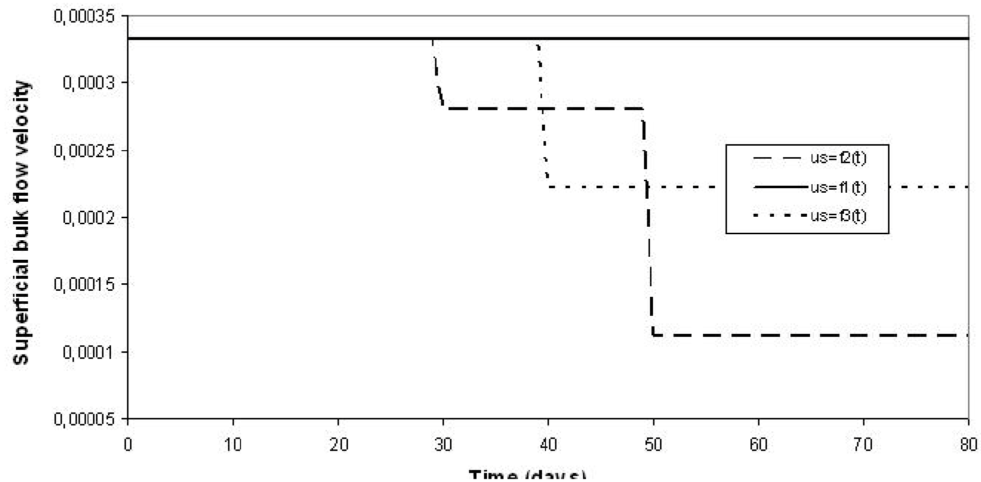


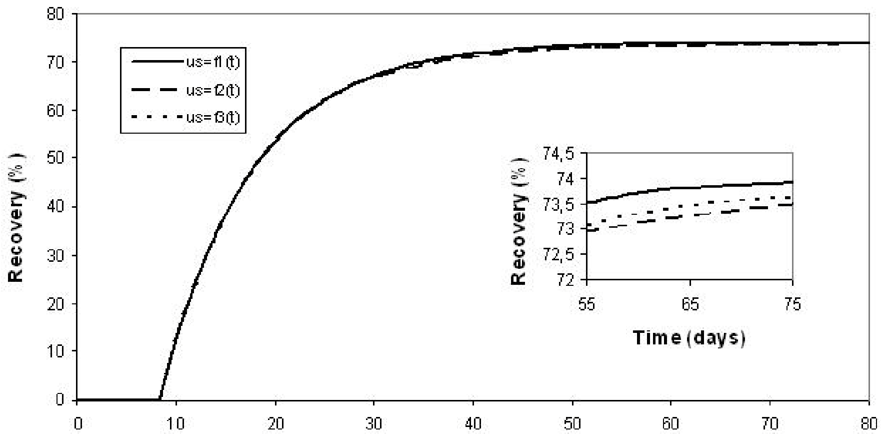


Post Modelling: Optimization of flow rates

$$\frac{\partial E}{\partial u_s} := E_\infty \left[\lambda k_t \left(\frac{w}{u_s} + \frac{(t - \tilde{w})}{Z \epsilon_b} \right) e^{-\psi_1} + \Lambda k_\theta \frac{D_{Ae} \tilde{w}}{R^2 \epsilon_{()} u_s} e^{-\psi_2} \right] .$$







Remark on Modelling in Mineral Process

- Designers and operators of minerals process have traditionally had to rely on empirical methods and field experience for design and troubleshooting.
- Empirical methods limit the options for engineers to improve the performance of process relative to the properties of ore and variation in design/operation conditions.
- Phenomenological models can be developed, however, they are more difficult to apply in industry applications due it is necessary to deal with rather complex mathematics or suppose an ideal behaviour, and need information that is difficult or impossible to measure (bulk particle systems).
- A third modelling approach is also possible. It consists in the combination of the two latter approaches. This approach leads to rather simple models but enough accurate for some applications (e.g. optimization, sensitivity analysis) and easy to transfer to practice.

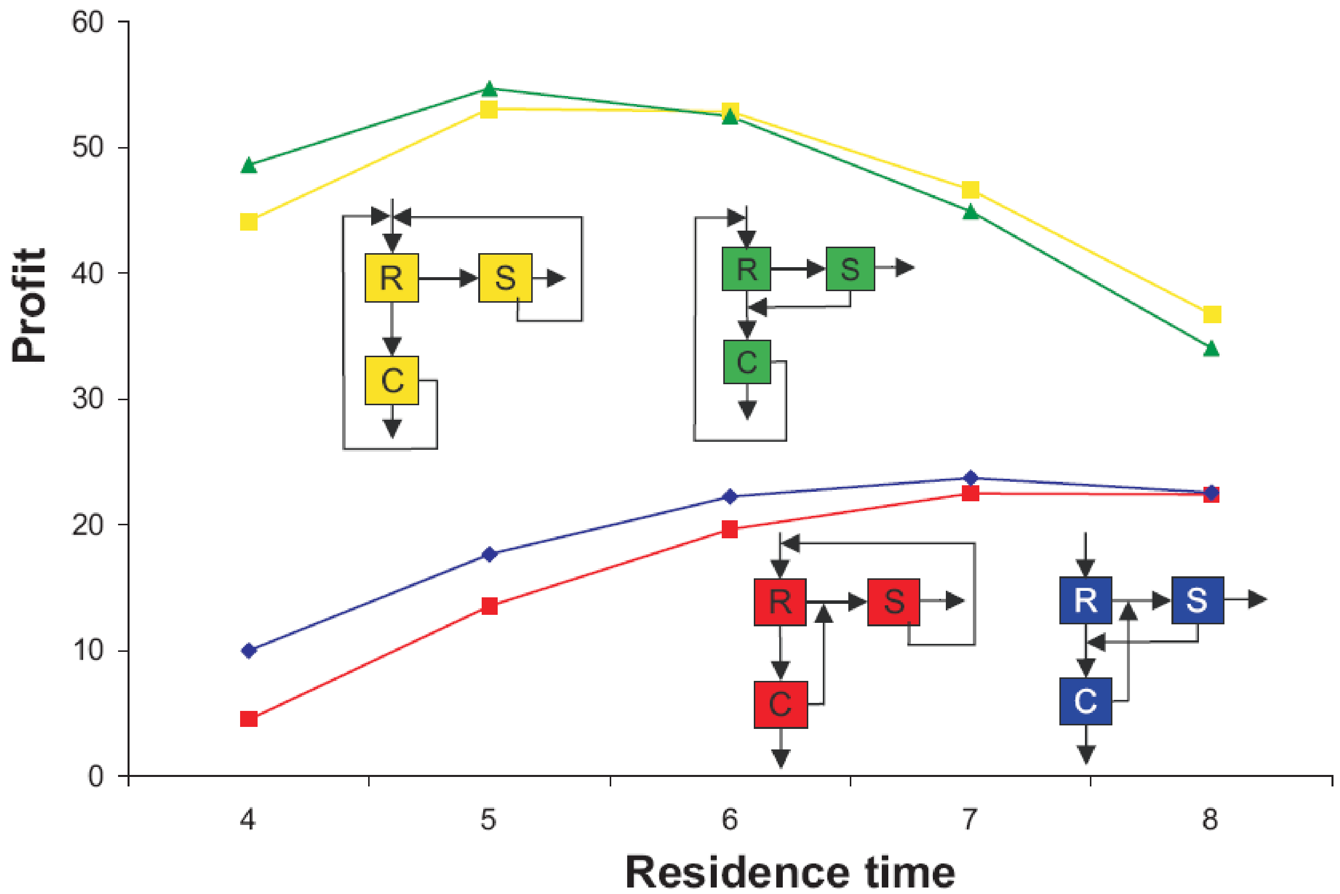
References on Heap Leaching Modelling

- Padilla GA, Cisternas LA, Cueto JY, On the optimization of heap leaching, Minerals Engineering , 21(9), 673-678, (2008).
- Mario E. Mellado, Luis A. Cisternas, An analytical–numerical method for solving a heap leaching problem of one or more solid reactants from porous pellets, Computers & Chemical Engineering, 32,(10), 2395-2402, (2008).
- John A. Valencia, David A. Méndez, Jessica Y. Cueto, Luis A. Cisternas, Saltpeter extraction and modelling of caliche mineral heap leaching, Hydrometallurgy, 90 (2-4), 103-114, (2008).
- Mario E. Mellado, Luis A. Cisternas, Edelmira D. Gálvez, An analytical model approach to heap leaching, Hydrometallurgy, 95 (1-2), 33-38 (2009).
- Mario E. Mellado, María P. Casanova, Luis A. Cisternas, Edelmira D. Gálvez, On scalable analytical models for heap leaching, Computers & Chemical Engineering, 35 (2), 220-225 (2011)

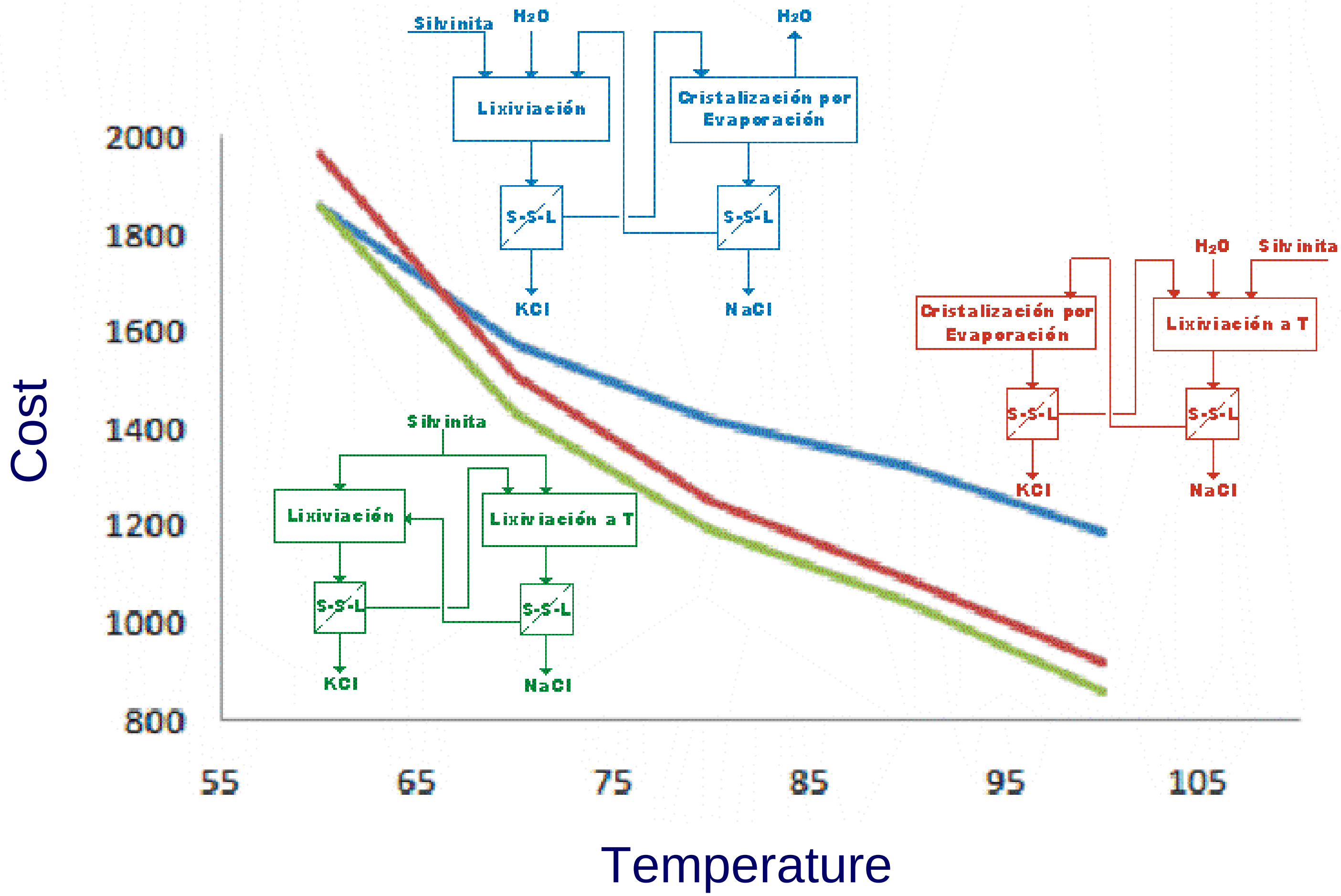
Methods for Process Synthesis

- Introduction
- Crystallization
- Flotation Design
- Flotation Analysis

Flotation Structural Optimization



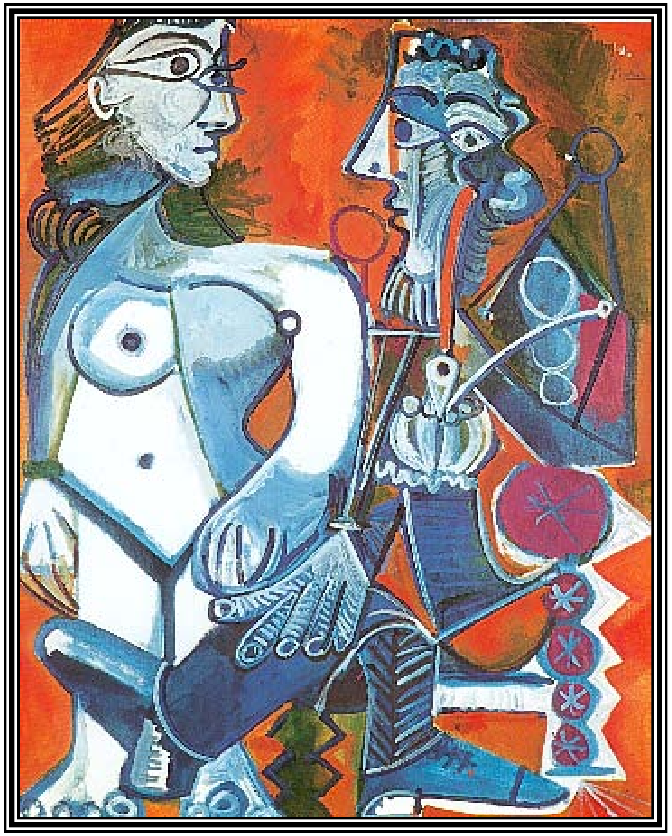
Crystallization Structural Optimization



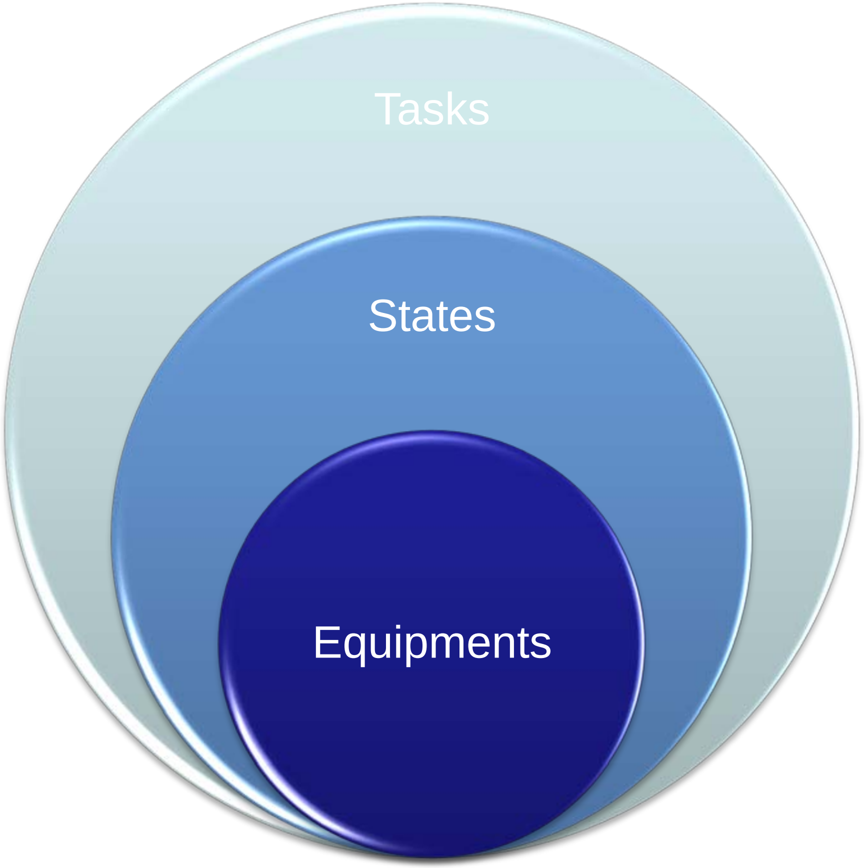
Dimensional Representation

Roberto Matta
Chilean 1911-2002

Mujer Desnuda de Pie
y Hombre Sentado con Pipa,
Pablo Picasso (Spanish)



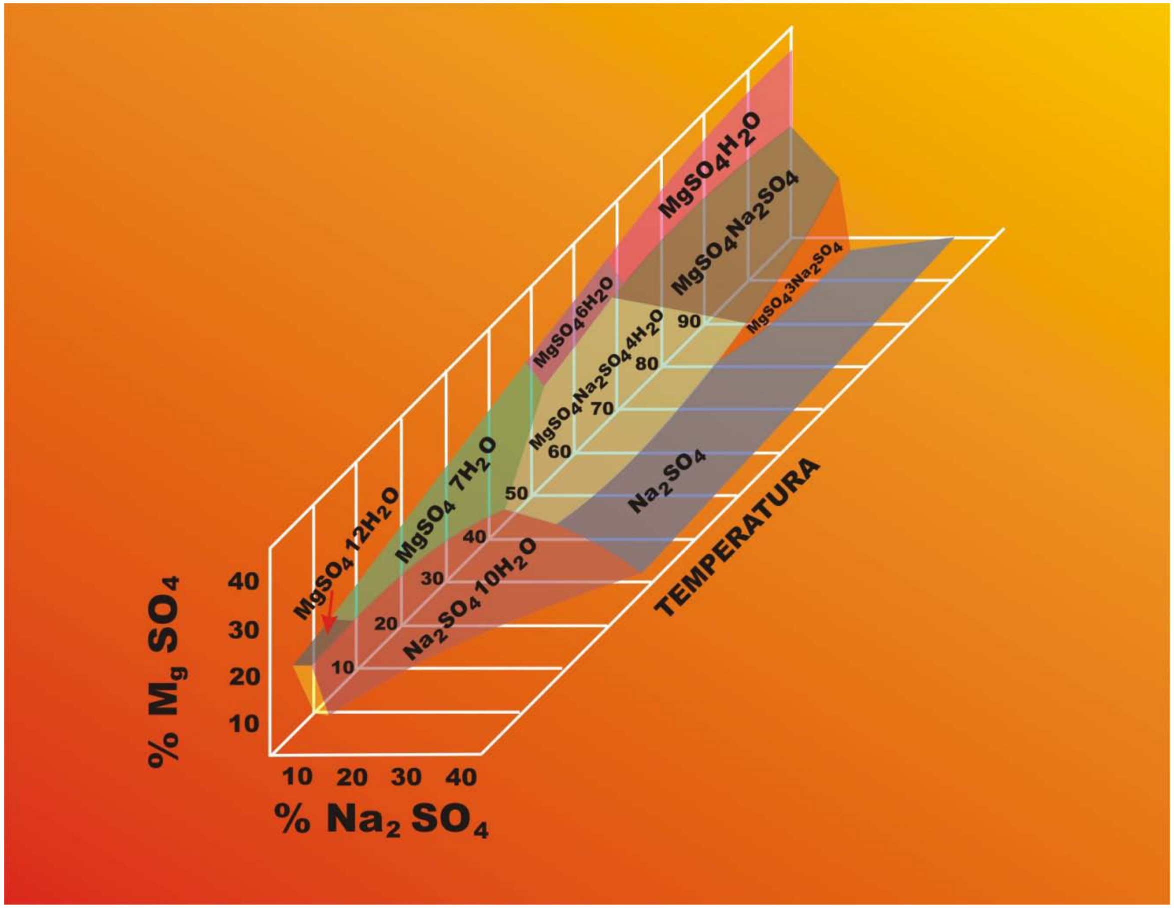
The Onion Model



Crystallization Design Problem

- Crystallization is extensively used in different industrial applications (fertilizers, detergents, foods, pharmaceutical products, treatment of waste effluents).
- The crystallization stages are usually accompanied by other separation techniques. Leaching.
- Various types of crystallization exist: cooling, evaporation, reactions, and drowning-out
- The characteristics of the product affects a series of other associated operations. filtration & washing.
- The separation is limited by multiple saturation points.

Phase Diagram



Introduction | Crystallization | Flotation Design | Flotation Analysis

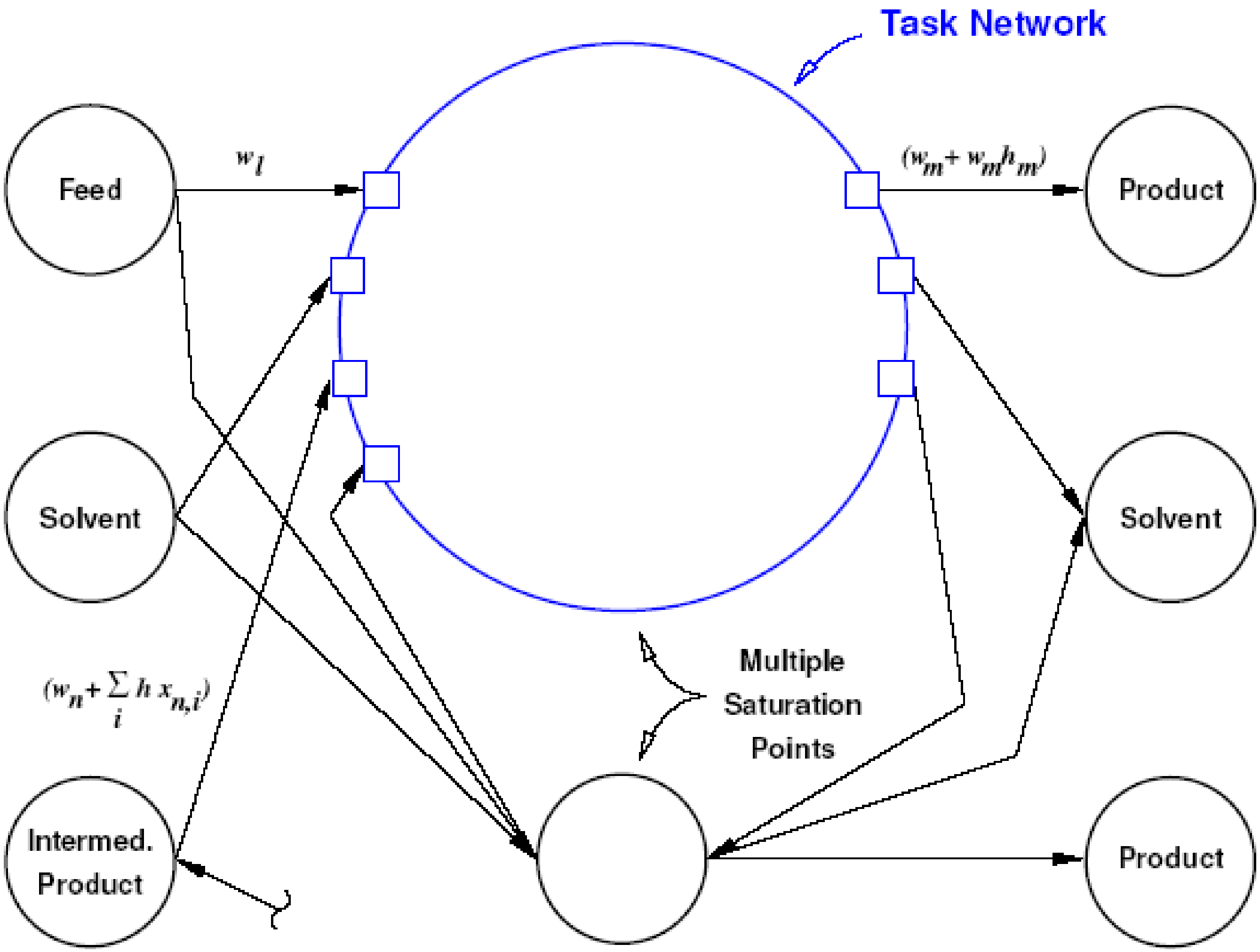
Example: Astrakanite

Equilibrium data for $MgSO_4$+Na_2SO_4+H_2O system.

T ºC	keys	Saturated solution, % w		Solid phase
		$MgSO_4$	Na_2SO_4	
18.7	C	20.57	11.8	Mg_7 + Na_{10}
25	D1	21.15	13	Mg_7 + SD1
25	D2	16.6	17.8	SD1 + Na_{10}
50	E1	31.32	4.74	Mg_6 + SD1
50	E2	11.98	23.25	SD1 + Na
97	F1	32.2	5.55	Mg_1 + SD2
97	F2	14.4	19.15	SD2 + SD3
97	F3	5.88	26.9	SD3 + Na
	SD1	35.99	42.48	
	SD2	45.86	54.14	
	SD3	22.02	77.98	

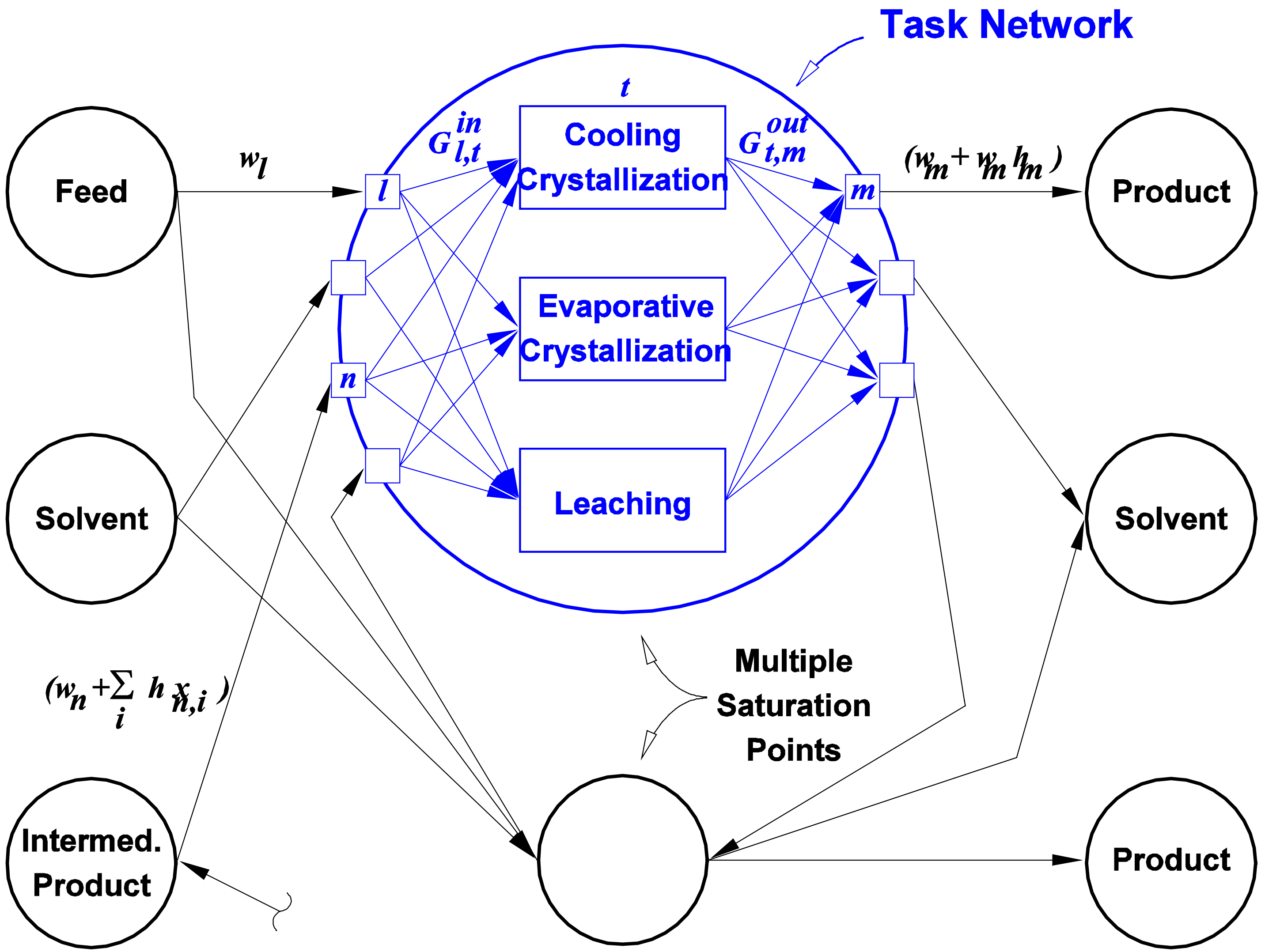
Mg7=MgSO4.7H2O; Mg1=MgSO4.1H2O; Mg6=MgSO4.6H2O; Na10=Na2SO4.10H2O; Na=Na2SO4; SD1= Na2SO4.MgSO4.4H2O; SD2= Na2SO4.MgSO4; SD3= MgSO4.3Na2SO4

State Superstructure

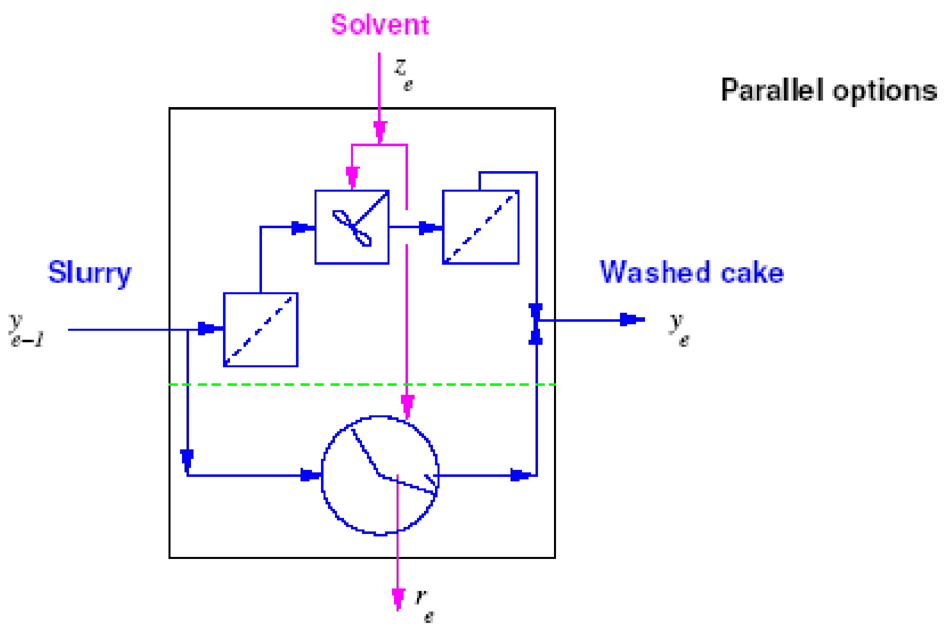


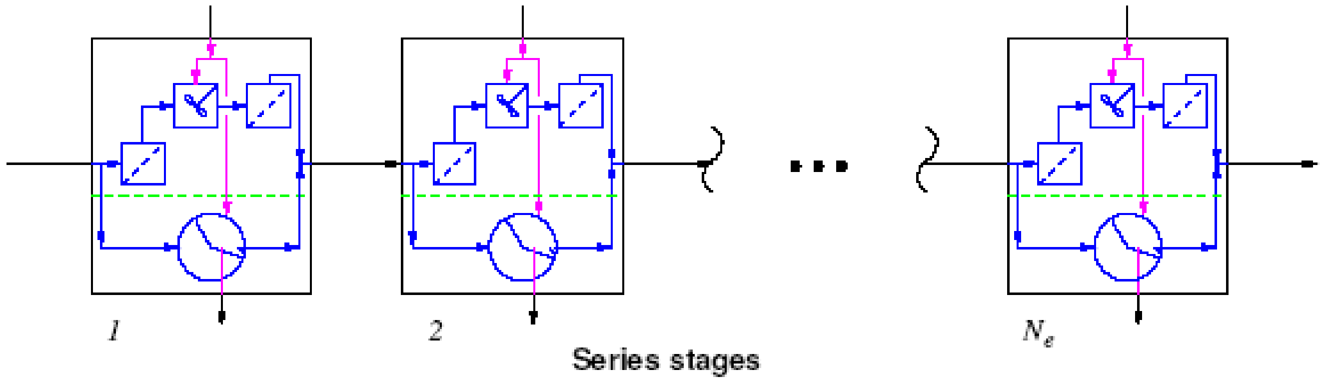
Introduction | Crystallization | Flotation Design | Flotation Analysis

Task Superstructure

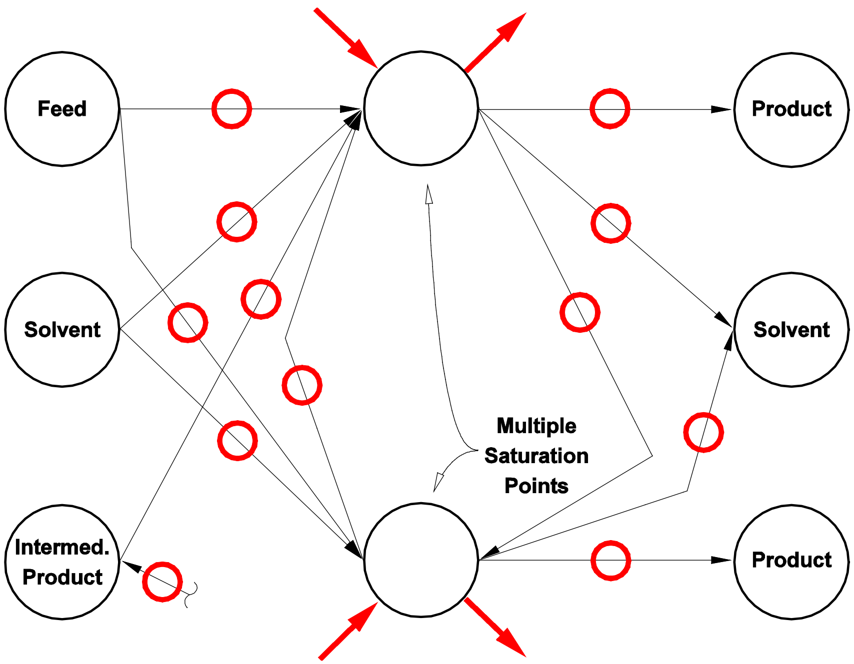


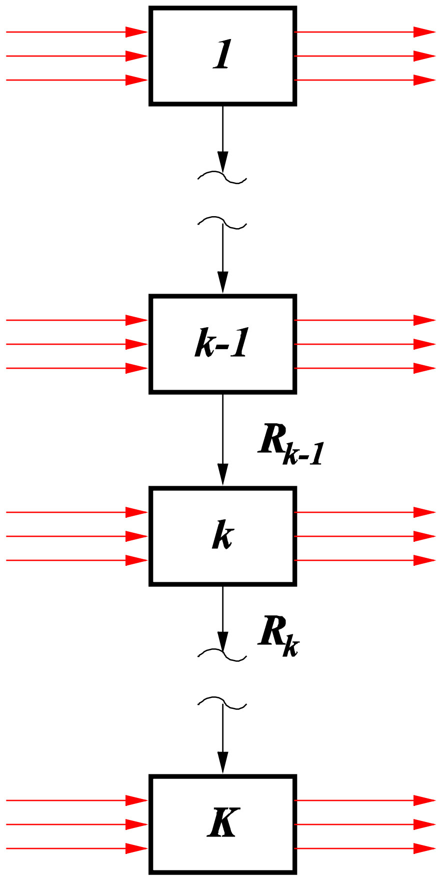
Cake-Washing Superstructure





Heat Integration Superstructure





Mathematical Model

State Superstructure

$$\sum_{l \in Lq \cap S^{in}(s)} w_l \cdot x_{l,i} - \sum_{l \in Lq \cap S^{out}(s)} w_l \cdot x_{l,i} = 0 \qquad s \in S_I, i \in I$$

Task Superstructure

$$\begin{bmatrix} y_{t,s} \\ FC_{t,s} = \alpha_{t,s} \\ VC_{t,s} = \beta_{t,s} \sum_{l \in S^{in}(s)} G^{in}_{l,t} \\ Q^C_{t,s} = HQ^C_{t,s} G^{out}_{t,l1} \\ Q^S_{t,s} = HS_{t,s} G^{out}_{t,l}, l \in S^{out}_s(s) \end{bmatrix} \vee \begin{bmatrix} \neg y_{t,s} \\ FC_{t,s} = 0 \\ VC_{t,s} = 0 \\ Q^C_{t,s} = 0 \\ Q^S_{t,s} = 0 \end{bmatrix} \quad t \in T(s), s \in S_M$$

$$g(y_{t,s}) = \text{True}$$

Cake Washing

$$\begin{bmatrix} yw_{l,e} \\ \neg yr_{l,e} \\ y_{l,e,i} = ymw_{l,e,i} \\ ypw_{l,e,i} = y_{l,e-1,i} \end{bmatrix} \vee \begin{bmatrix} \neg yw_{l,e} \\ yr_{l,e} \\ y_{l,e,i} = ymr_{l,e,i} \\ ypr_{l,e,i} = y_{l,e-1,i} \end{bmatrix} \vee \begin{bmatrix} \neg yw_{l,e} \\ \neg yr_{l,e} \\ y_{l,e,i} = y_{l,e,i} \\ ymr_{l,e,i} = 0 \end{bmatrix} \qquad \begin{matrix} e \in E(Lw), \\ l \in Lw, i \in I \end{matrix}$$

Heat Integration

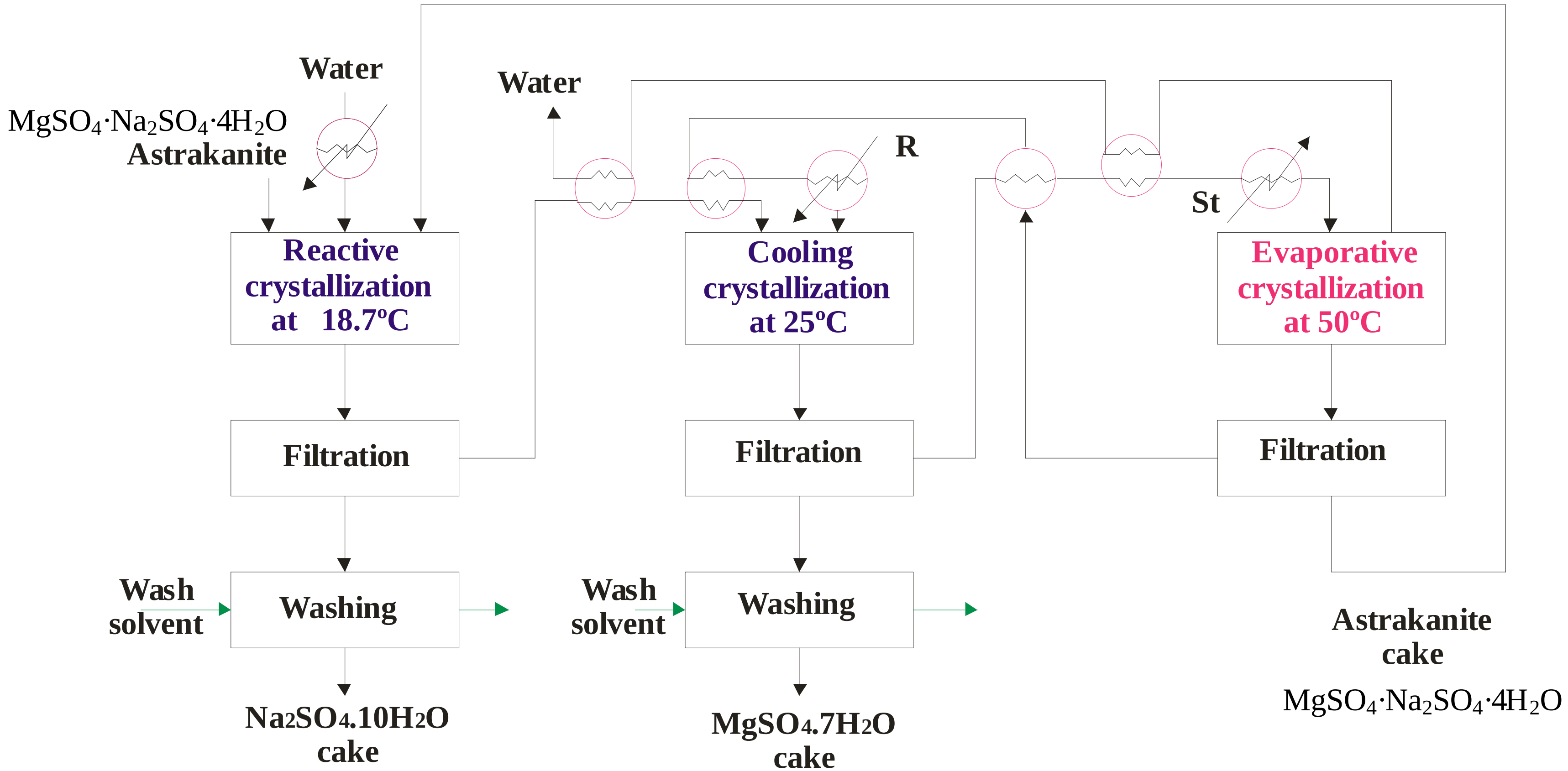
$$R_k - R_{k-1} - \sum_{m \in V_k} Q^V_m + \sum_{n \in U_k} Q^U_n = \sum_{l \in H_k} w_l \, (C_p \Delta T)^H_{lk} - \sum_{l \in C_k} w_l \, (C_p \Delta T)^C_{lk} \qquad k \in K$$

Objective Function

$$\min \sum_{s \in S_M} \sum_{t \in T(s)} (FC_{t,s} + VC_{t,s} + c^C_{t,s} Q^C_{t,s} + c^S_{t,s} Q^S_{t,s}) + \sum_{m \in V} c_m Q^V_m + \sum_{n \in U} c_n Q^U_n + \sum_{l \in Lw} \sum_{e} (Cf_{l,e} + Cv_{l,e})$$

Example: Astrakanite ($MgSO_4.Na_2SO_4.4H_2O$)

The MILP formulation contains 1209 equations, 1201 continuous variables, and 145 binary variables. Solution time was 84 s for OSLv2 (GAMS) with a 1.7 GHz Pentium 4 processor.



Comments on Fractional Crystallization

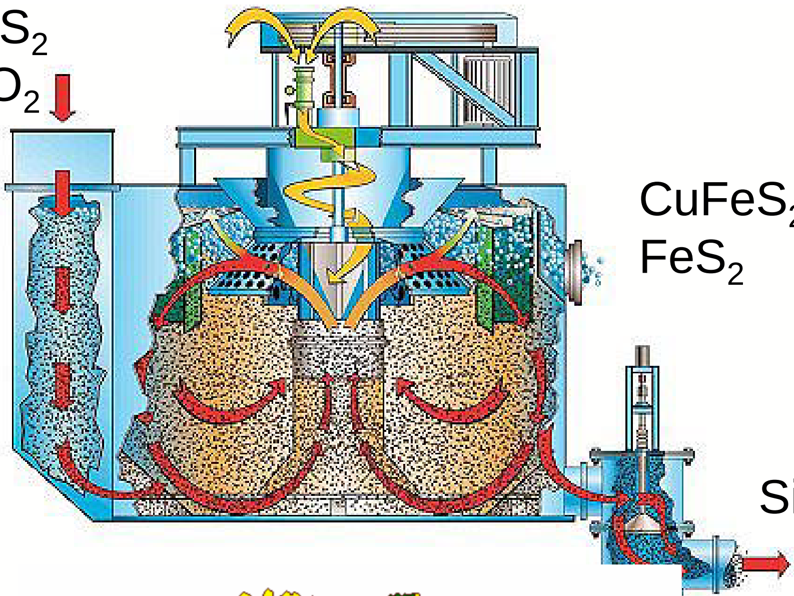
- Over the last 20 years significant advances have been achieved in methods for the design and improvement of separation processes based on fractional crystallization.
- These advances have addressed the separation of simple systems, systems involving the formation of compounds, drowning-out, metathetic salts, hybrid processes, environmental applications and multicomponent systems.
- Important advances have been made in the use of phase diagrams as design tools, especially with respect to the visualization of multicomponent systems.
- Procedures for the conceptual design of these systems have been divided into two schools of thought. One group of researchers used hierarchical procedures based on rules, whereas others used superstructures that represent different possibilities for processing, applying a mathematical model for identification of the most useful approach to each problem.

References on Fractional Crystallization Design

- Cisternas L.A., D. F. Rudd, 1993, Process design for fractional crystallization from solution, Ind. Eng. Chem. Res., 32, 1993-2005
- Cisternas L.A., R.E. Swaney, 1998, Separation system synthesis for fractional crystallization from solution using a network flow model, Ind. Eng. Chem. Res., 37, 2761-2769.
- Cisternas L.A., 1999, Optimal design of crystallization-based separation schemes, AIChE J., 45, 1477-1487.
- Cisternas L.A., C.P. Guerrero, R.E. Swaney, 2001, Separation system synthesis of fractional crystallization processes with heat integration, Comput. Chem. Engng., 25, 595-602.
- Cisternas L.A., M.A. Torres, M.J. Godoy, R.E. Swaney, 2003, Design of separation schemes for fractional crystallization of metathetical salts, AIChE J., 49 (7), 1731-1742
- Cisternas L.A., J. Cueto, R. E. Swaney, 2004, Flowsheet synthesis of fractional crystallization processes with cake washing, Comput. Chem. Engng., 28, 613-623.
- Cisternas LA, Vasquez CM, Swaney RE, On the design of crystallization-based separation processes: Review and extension, AIChE J., 52 (5) , 1754-1769.
- Ossandón K., Pinto P., Cisternas L.A., 2010, Planning and scheduling of salt harvest in solar evaporation ponds, Computers & Chemical Engineering, 34, 5, 620-630.

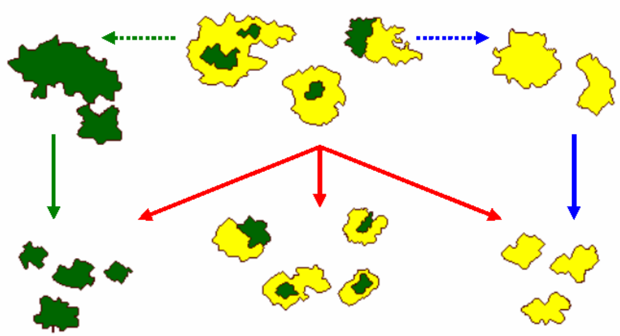
Flotation Circuit Design Problem

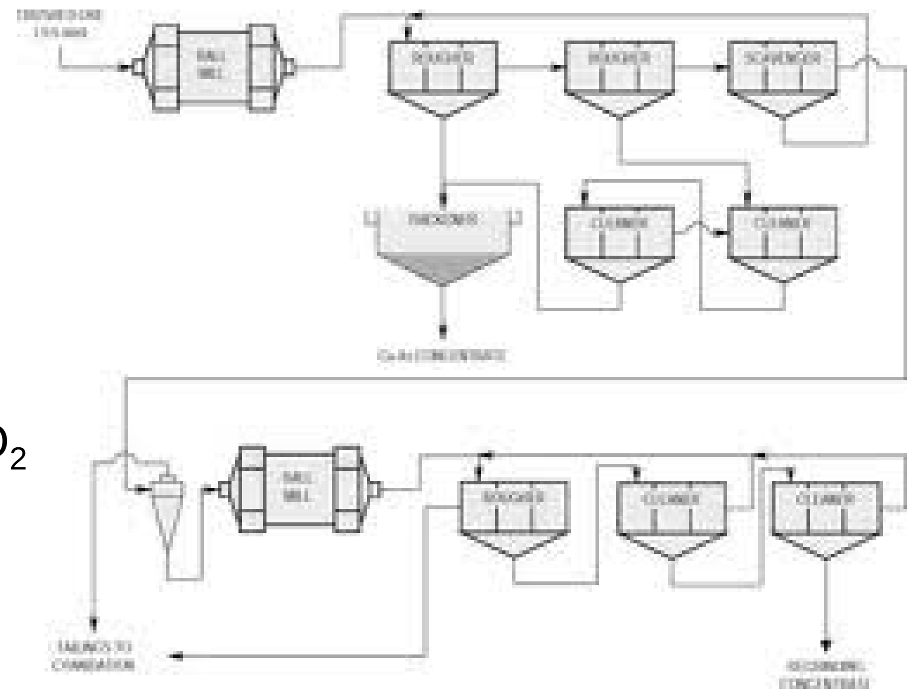
$CuFeS_2$
FeS_2
SiO_2



$CuFeS_2$
FeS_2

SiO_2





Introduction | Crystallization | Flotation Design | Flotation Analysis

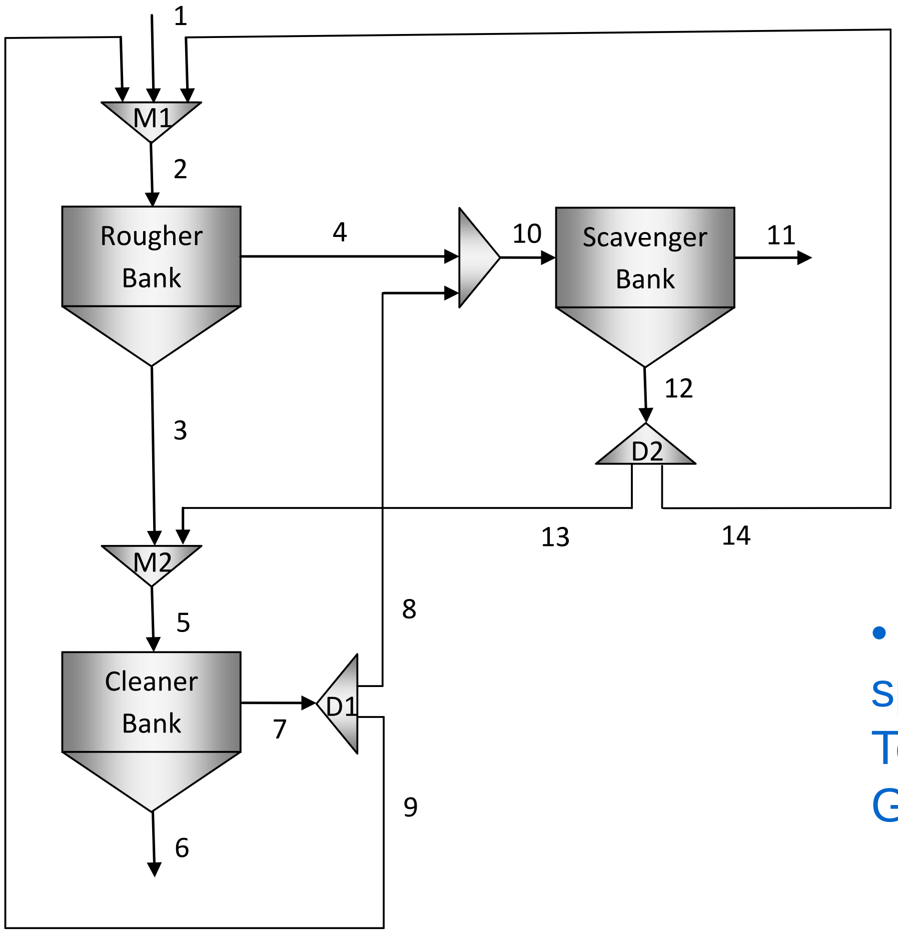
Flotation Circuit Design Problem

- Mineral flotation processes consist of several units that are grouped into banks and interconnected in a predefined manner in order to divide the feed into concentrate and tailing.
- The behavior of these processes depends on the configuration of the circuit and the physical and chemical nature of the slurry treated
- The design of these circuits is carried out based on the experience of the designer, with the help of laboratory tests and simulations.
- Some attempts have been described in the literature on automated methods for the design of these types of circuits.
- Methods for the design of flotation circuits have not yet progressed to the stage where an optimum circuit configuration can be completely derived automatically.
- Estimation of flotabilities of particle classes is probably the most challenging aspect in flotation modelling.

Flotation Circuit Design under Uncertainty

- Stochastic programming is applied to the design of mineral flotation circuits and compared them with results obtained by using deterministic programming (mean values of design parameters).
- In the optimization problem, it is desired to find the optimal configuration, equipment design (cell volume and cell number for each stage) and operational conditions (residence time) of a circuit with three stages: rougher, scavenger and cleaner.
- The problem includes uncertainty in the feed composition and in the metal price. Each uncertain parameter is characterized probabilistically using scenarios with different occurrence probabilities.

Superstructure of flotation circuit



- The feed has three mineralogical species: Chalcopyrite ($CuFeS_2$), Tennantite ($Cu_{12}As_4S_{13}$) and Gangue (SiO_2+Al_2O_3).

Introduction | Crystallization | **Flotation Design** | Flotation Analysis

Mathematical Model

MINLP

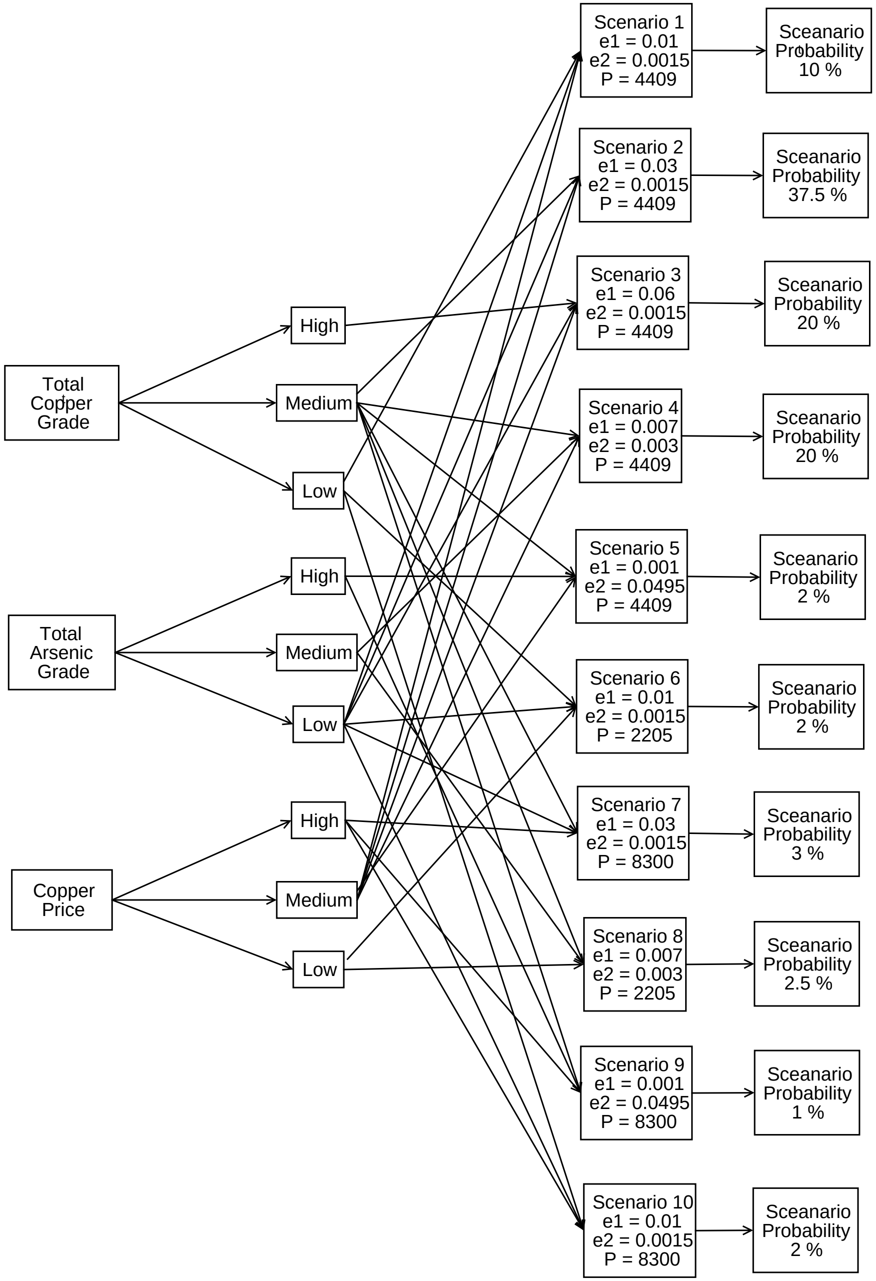
$$\max inc_1 - c_1 - c_{As,1} - fc$$

stochastic MINLP

$$\max \; -fc + \sum_{s \in S} P_s \cdot (inc_s - c_s - c_{As,s})$$

s.t.

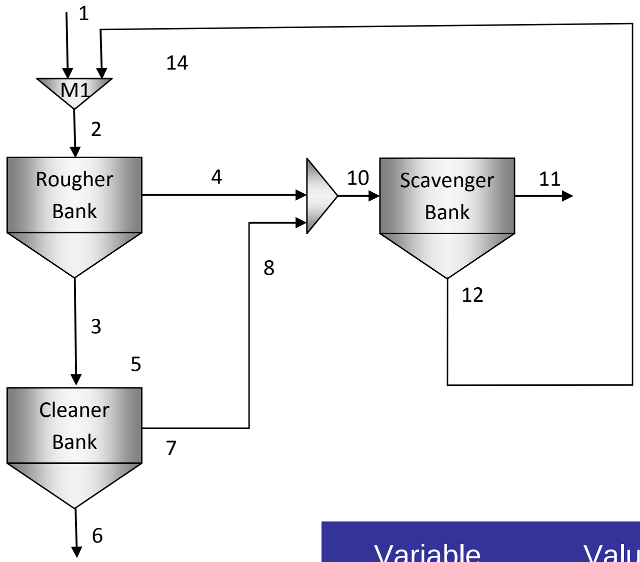
- Mass Balance
- Kinetics of flotation
- Arsenic penalization
- Cell volume
- Bounds
- Cost
- Income



Variability of uncertainty parameters represented in ten scenarios. e1 and e2 are chalcopyrite and tennantite feed grade. P copper price in US$/Ton.

- The average data considered are: Chalcopyrite grade 2.72 %, Tennantite grade 0.3 % and gangue grade 96.96 %, which implies a total copper grade of 1.11 % and arsenic grade of 0.02 % in the feed stream. The average copper price is 4,444 US$/Ton.

Deterministic Model



- The simulation delivers an income of 1.319 × 10^9 U.S.$/y.
- The real expected income is the weighted average of the incomes determined by evaluating on each scenario the design and operational variables. We found that the real expected income is about 4.5% less than given by the simulation, 1.263 ×10^9 U.S. $/y.

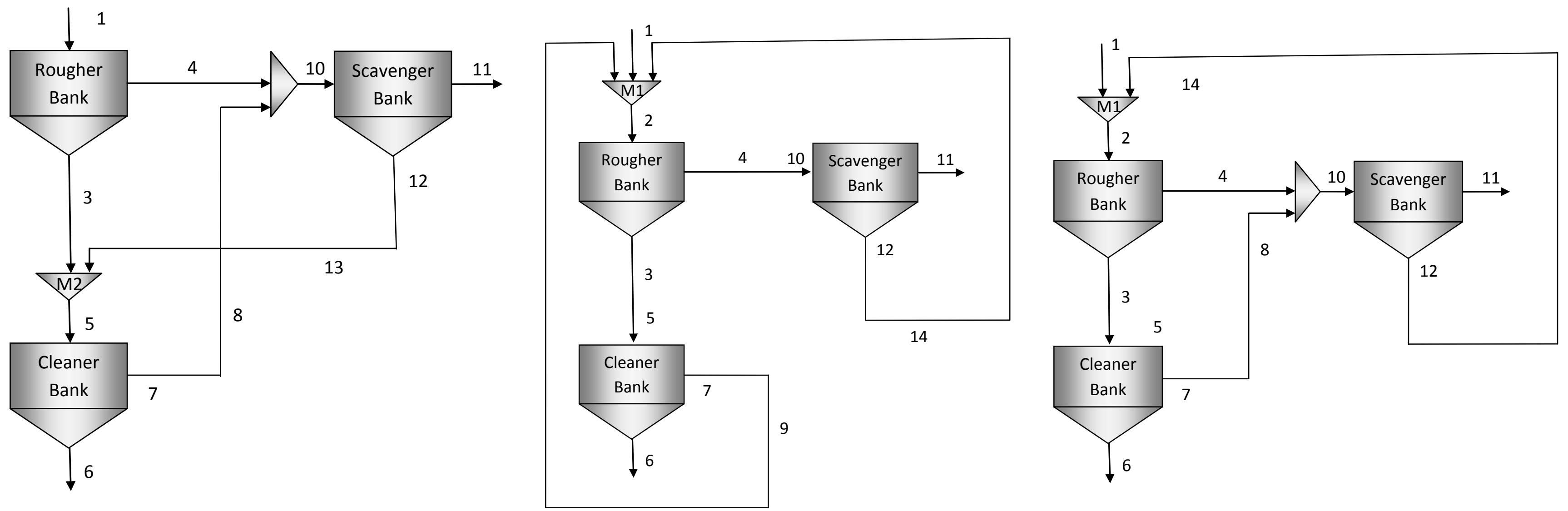
Variable	Value	Units	Variable	Value	Units
r_R	0.014	h	n_S	20	-
r_S	0.013	h	n_C	20	-
r_c	0.082	h	As grade	1.1	%
v_R	300	ft^3	Cu grade	18.1	%
v_S	300	ft^3	Deterministic Income	1.319×10^9	US$/y
v_C	273.697	ft^3	Real Expected Income	1.263×10^9	US$/y
n_R	20	-			

Stochastic Model

Variable	Scenario									
	1	2	3	4	5	6	7	8	9	10
$r_{S.R}$ (h)	0.015	0.015	0.015	0.015	0.015	0.012	0.015	0.015	0.015	0.014
$r_{S.S}$ (h)	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
$r_{S.C}$ (h)	0.047	0.066	0.061	0.047	0.064	0.026	0.066	0.031	0.064	0.066
$y_{S.1}$	1	1	1	1	1	0	1	1	1	1
$y_{s.2}$	1	1	1	1	1	0	1	1	1	0
As grade	1%									
Cu grade	18.3%									
Real Expected Income US$/y	1.39×10^{9}									

- The real expected income is 1.39×10^{9} US. $/y. This means to increase the income by 10% (130×10^{6} US. $/y) if it is compared with the deterministic model.
- Design variables for this case are 20 cells for each stage with a cell volume for each stage of 300 ft^3.
- The residence time for the scavenger stages is 0.013 h. for all scenarios. Rougher and cleaner residence times are flexible to each scenario.

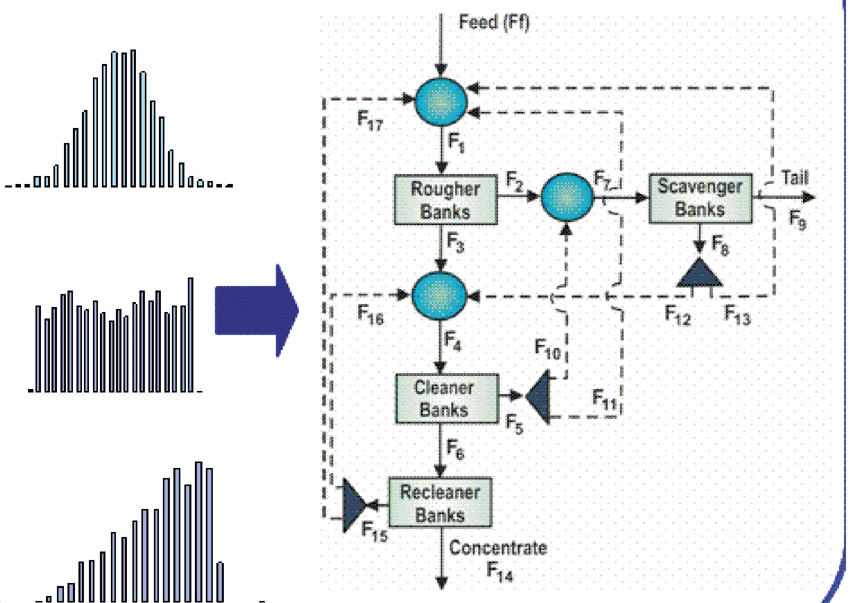
Stochastic Model

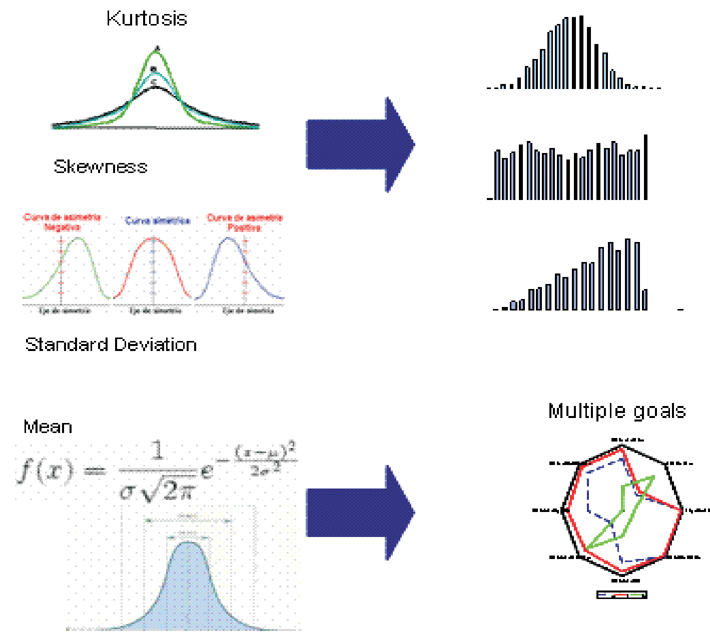


• if the price of metal is low, besides having a small operating time for the cleaner stage, it should recycle the cleaner tail and scavenger concentrate to the rougher stage. This is aimed at trying to remove impurities from the pulp that goes to the cleaner stage.

•if the price of metal is high, it is also necessary recirculation of the concentrate from scavenger stage to rougher stage, but the cleaner tail is re-circulated to the rougher stage for cleaning. The increased operating time of the cleaner stage will increase the recovery of both copper and other species, but due to high metal prices, it remains the most convenient option.

ANALYSIS OF UNCERTAINTY IN FLOTATION CIRCUITS





Variables

Indicators

Spider Graphics

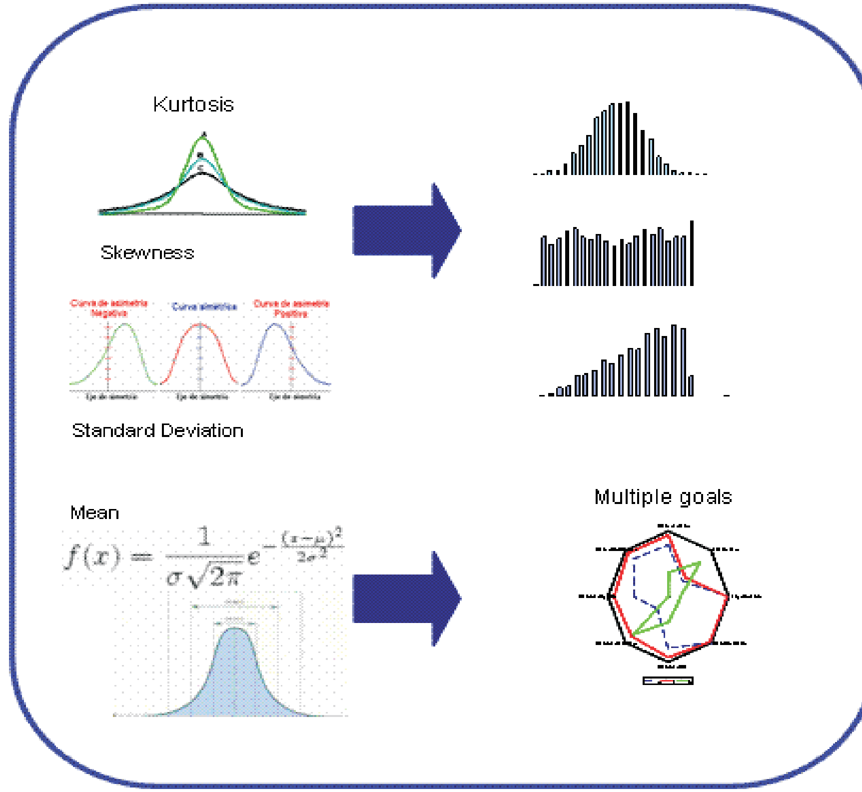
Monte Carlo Simulation

Post-simulation Analysis

INDICATORS

Technical
- Concentrate Grade
- Separation Factor
- Beneficiation factor
- Recovery

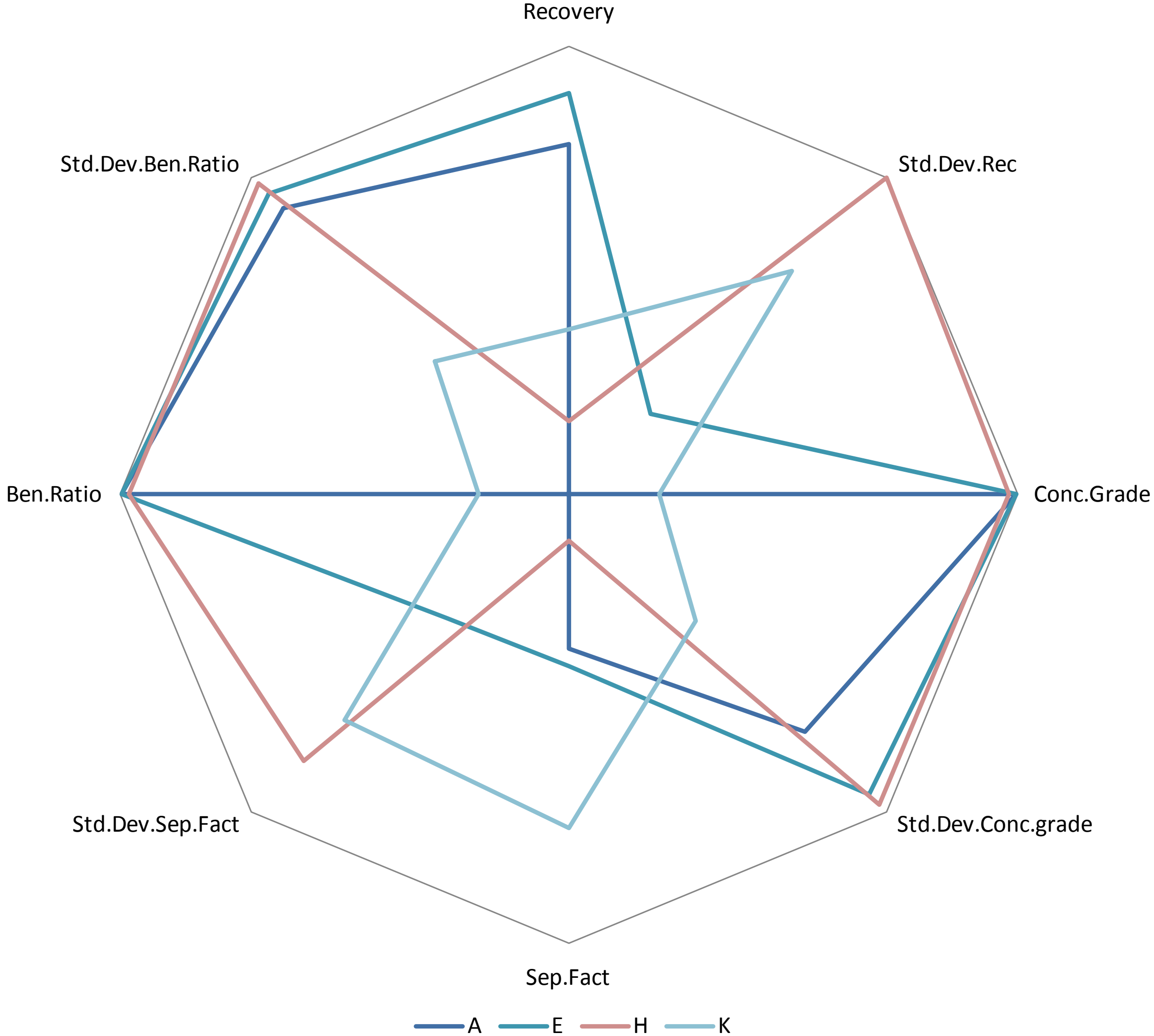
Statistical
- Mean
- Standard deviation
- Kurtosis
- Skewness



Indicators

Spider Graphics

RESULTS



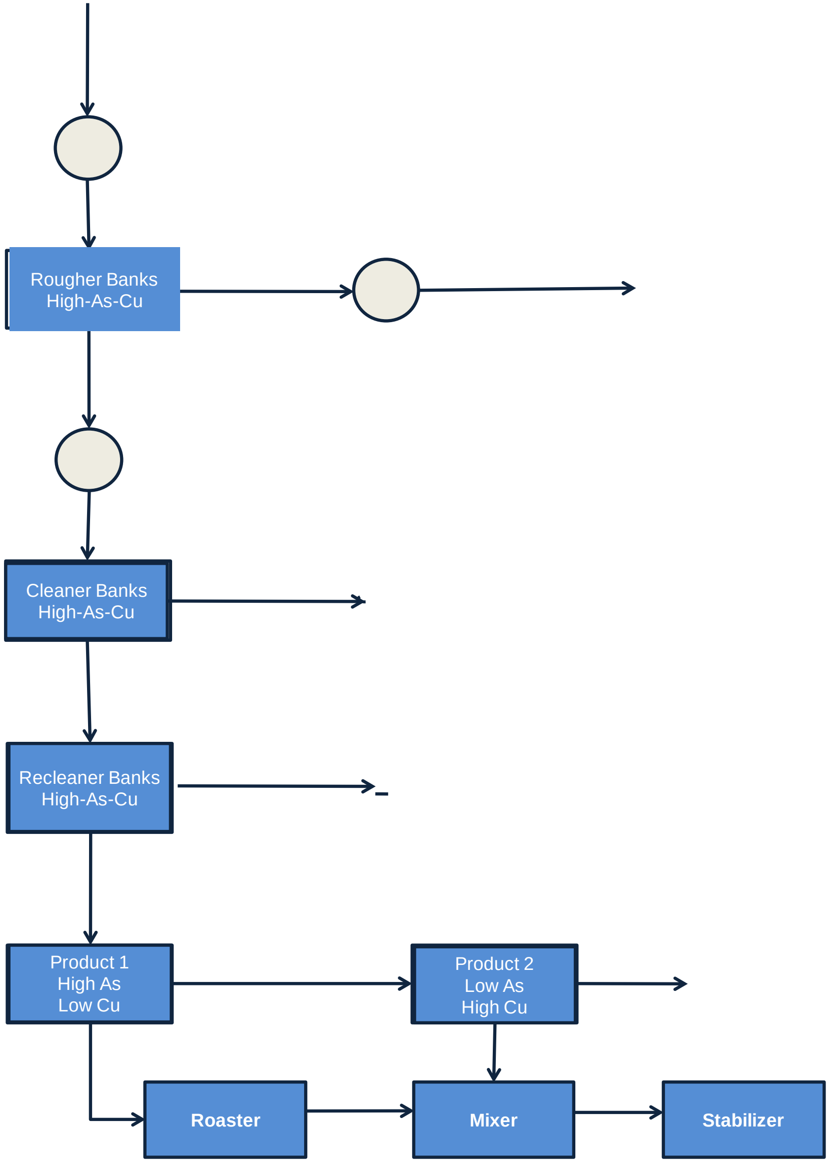
$$I_P = \frac{P - P_{\min}}{P_{\max} - P_{\min}}$$

Introduction
Crystallization
Flotation Design
Flotation Analysis

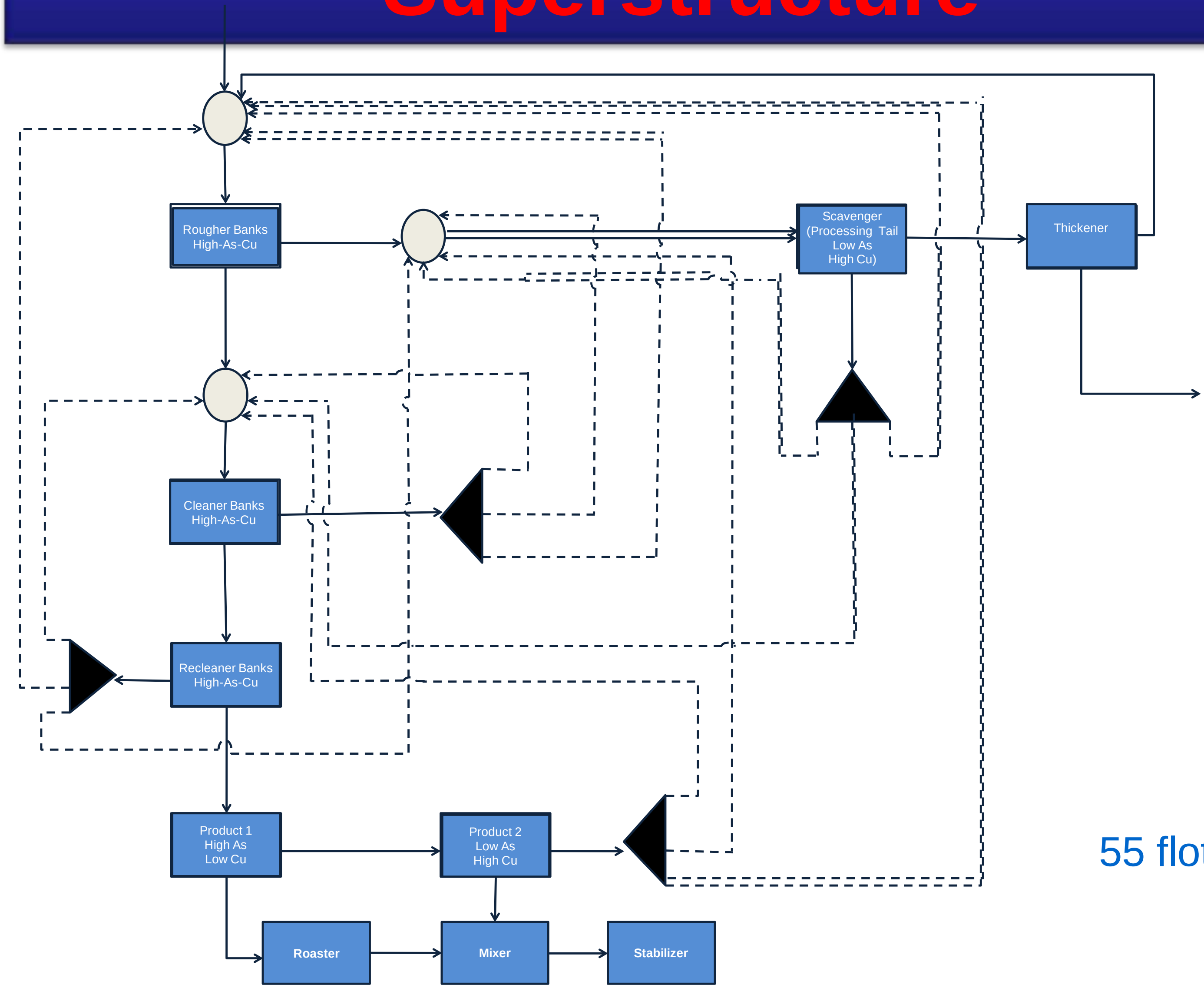
PROCESS RETROFIT

- Analyze the separation of copper and arsenic in the system Chalcopyrite ($CuFeS_2$), Tennantite ($Cu_{12}As_4S_{13}$) , Quartz.

- Process of CSIRO-Australia

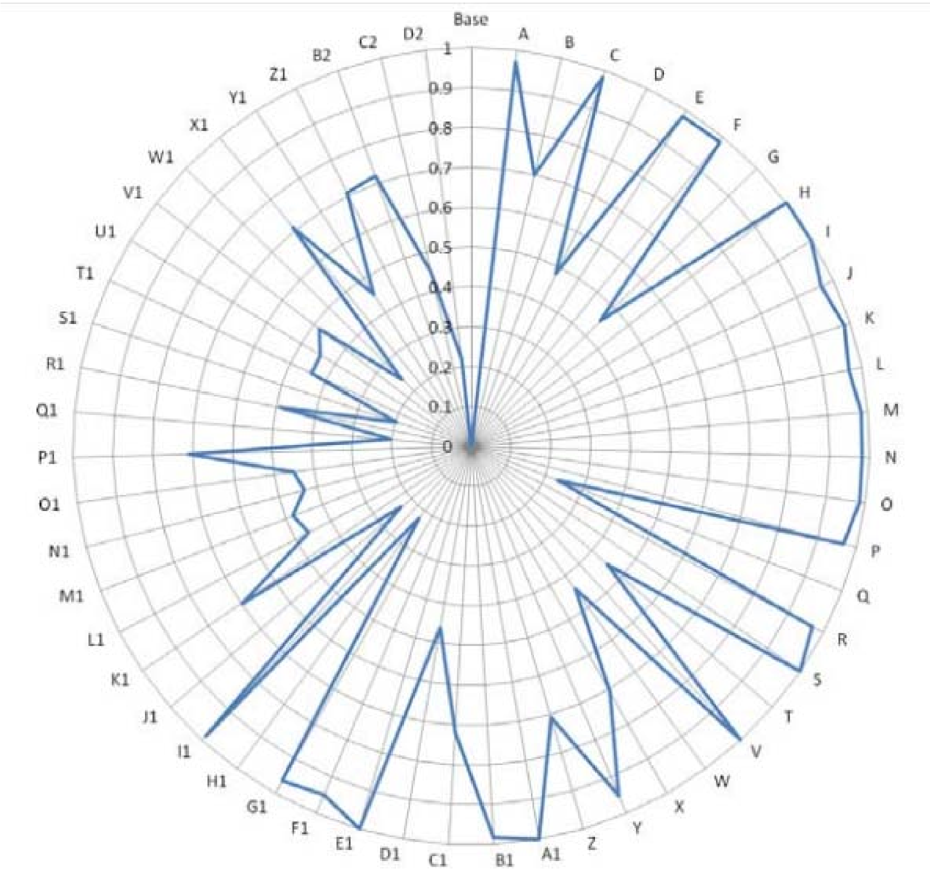


Superstructure

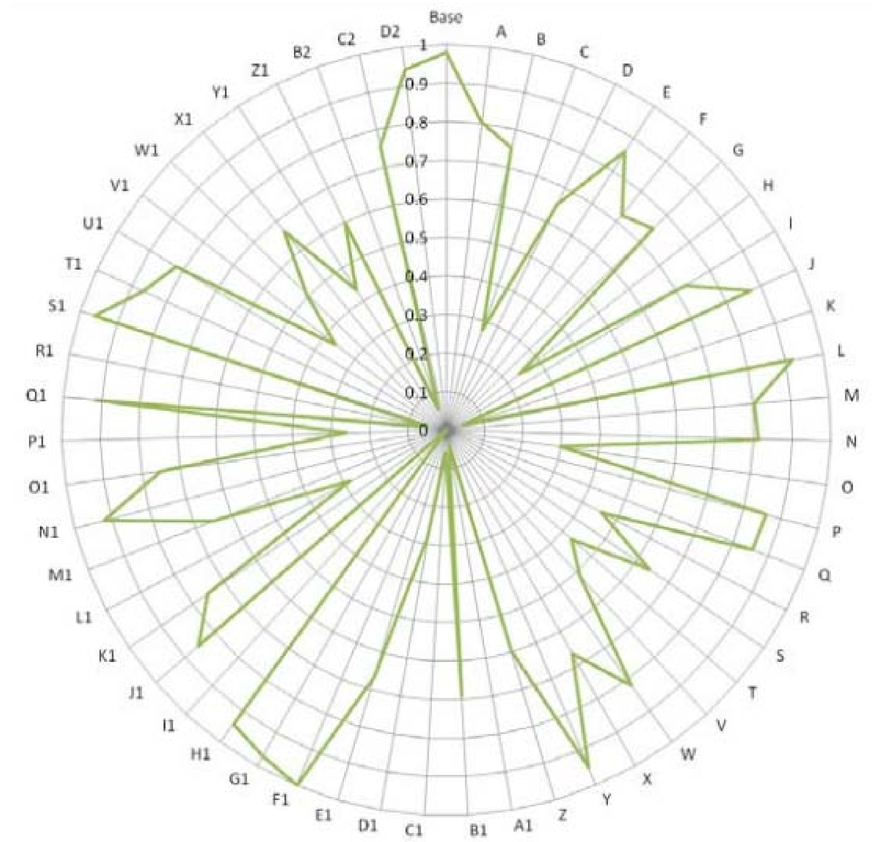


55 flotation circuits

Technical Indicators

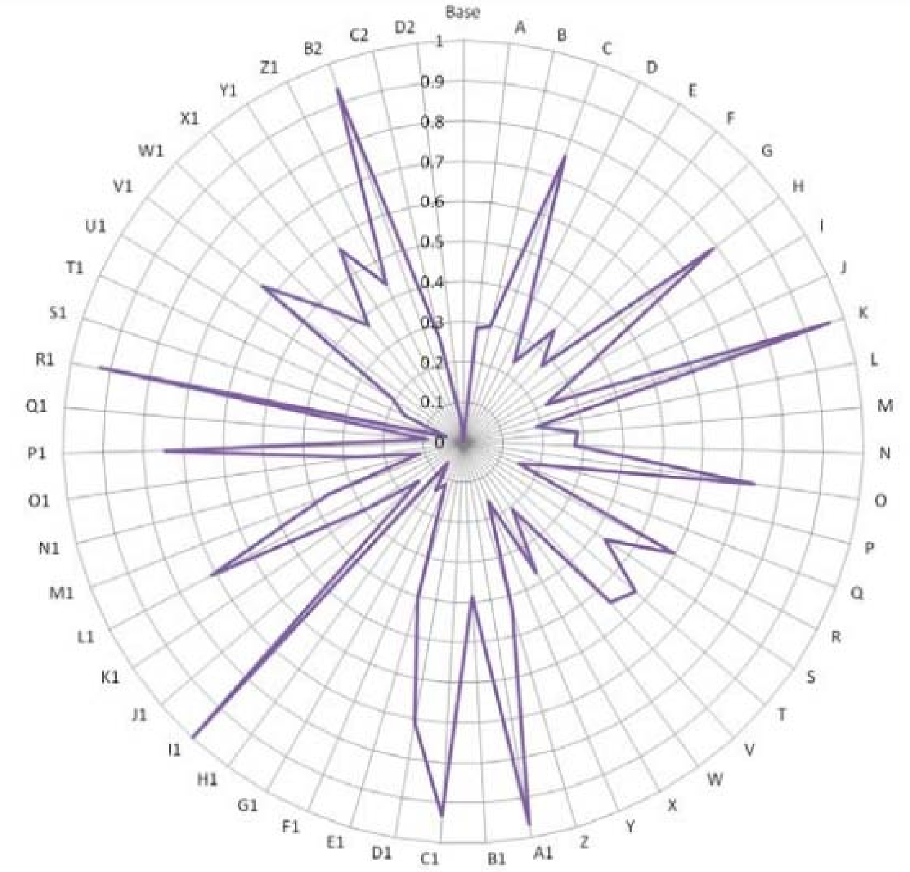


Global Copper Recovery

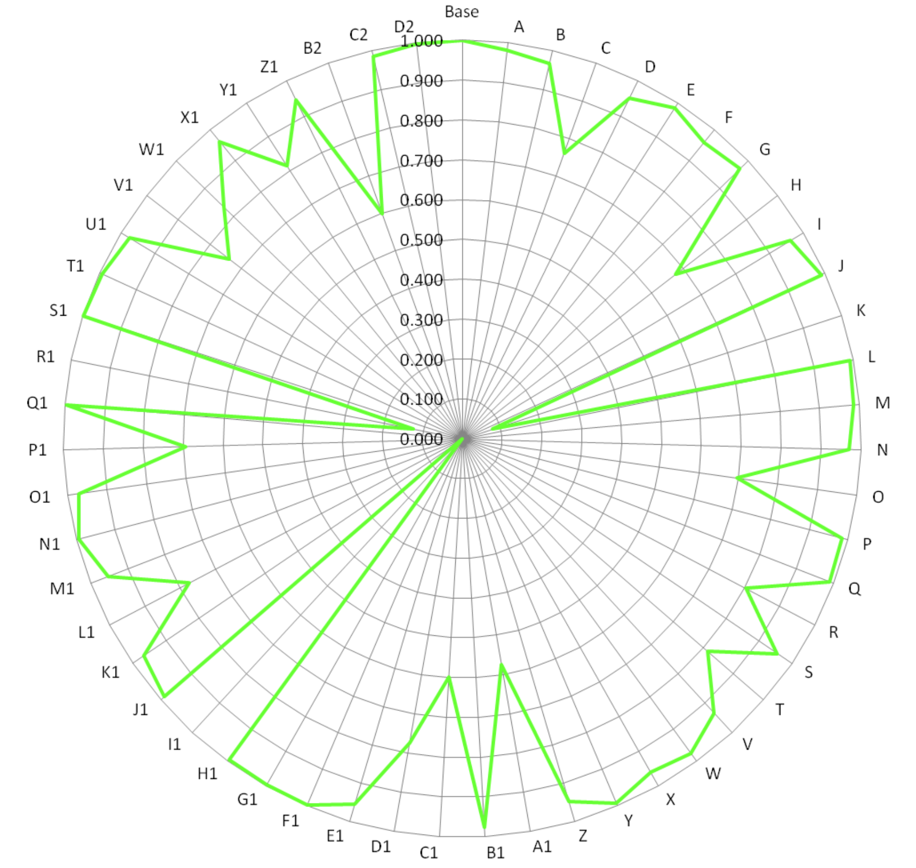


Copper Concentrate grade

Environmental Indicators



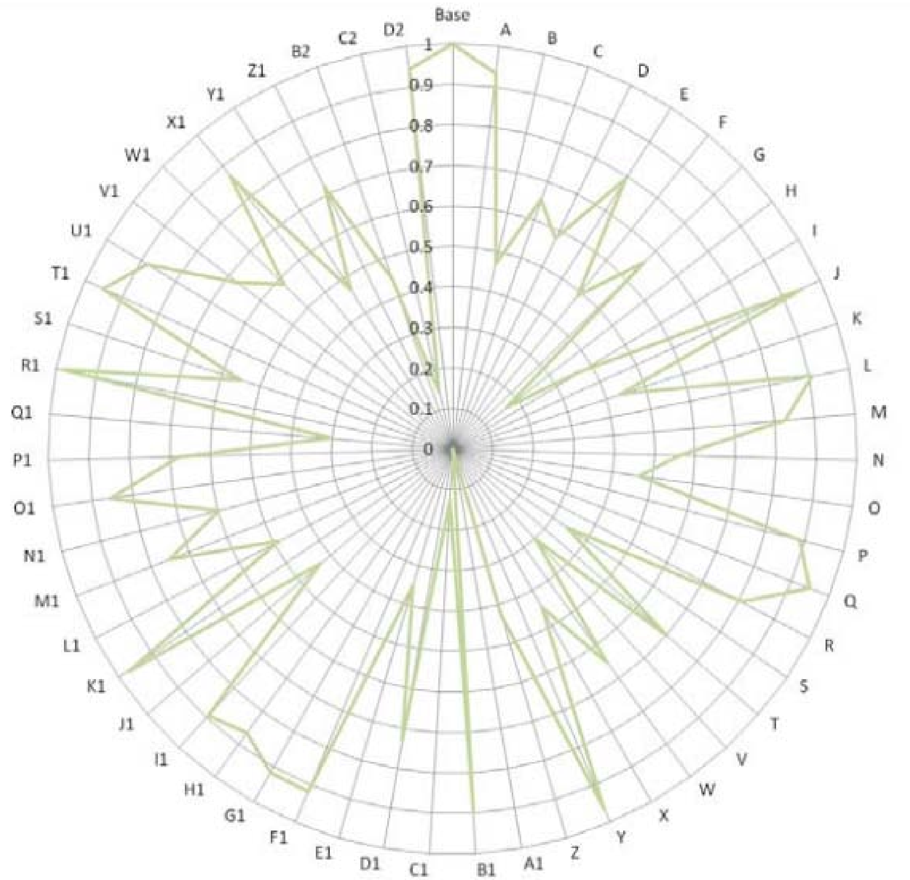
Arsenic in the product



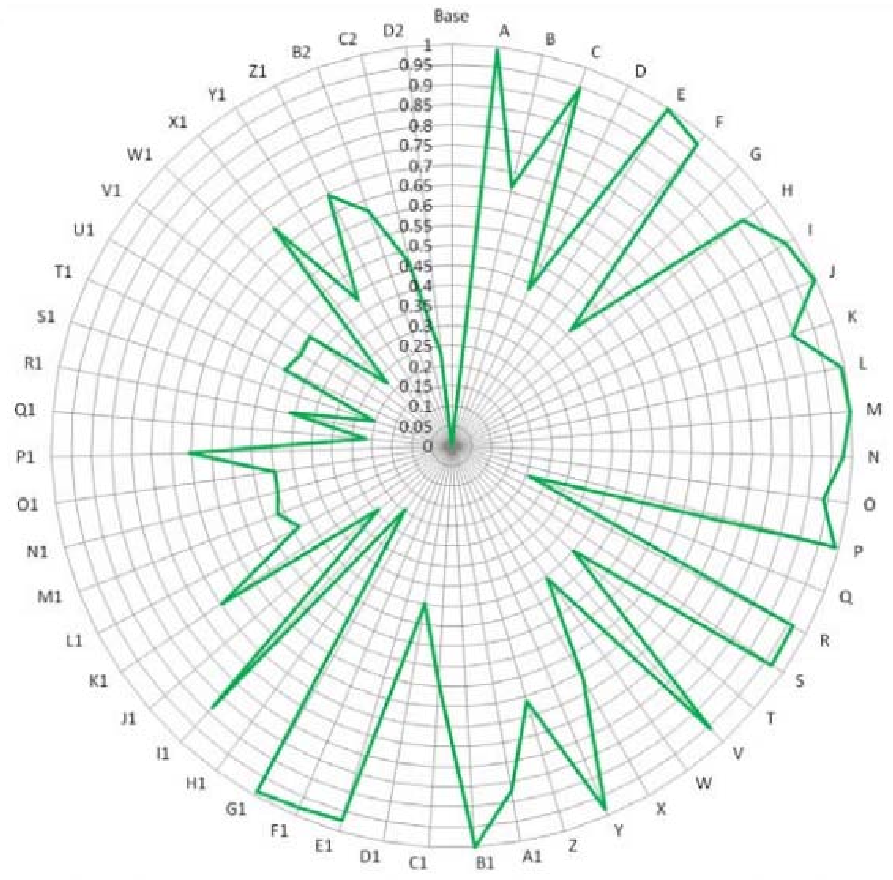
Fresh water usage

Introduction | Crystallization | Flotation Design | **Flotation Analysis**

Environmental & Economical Indicators

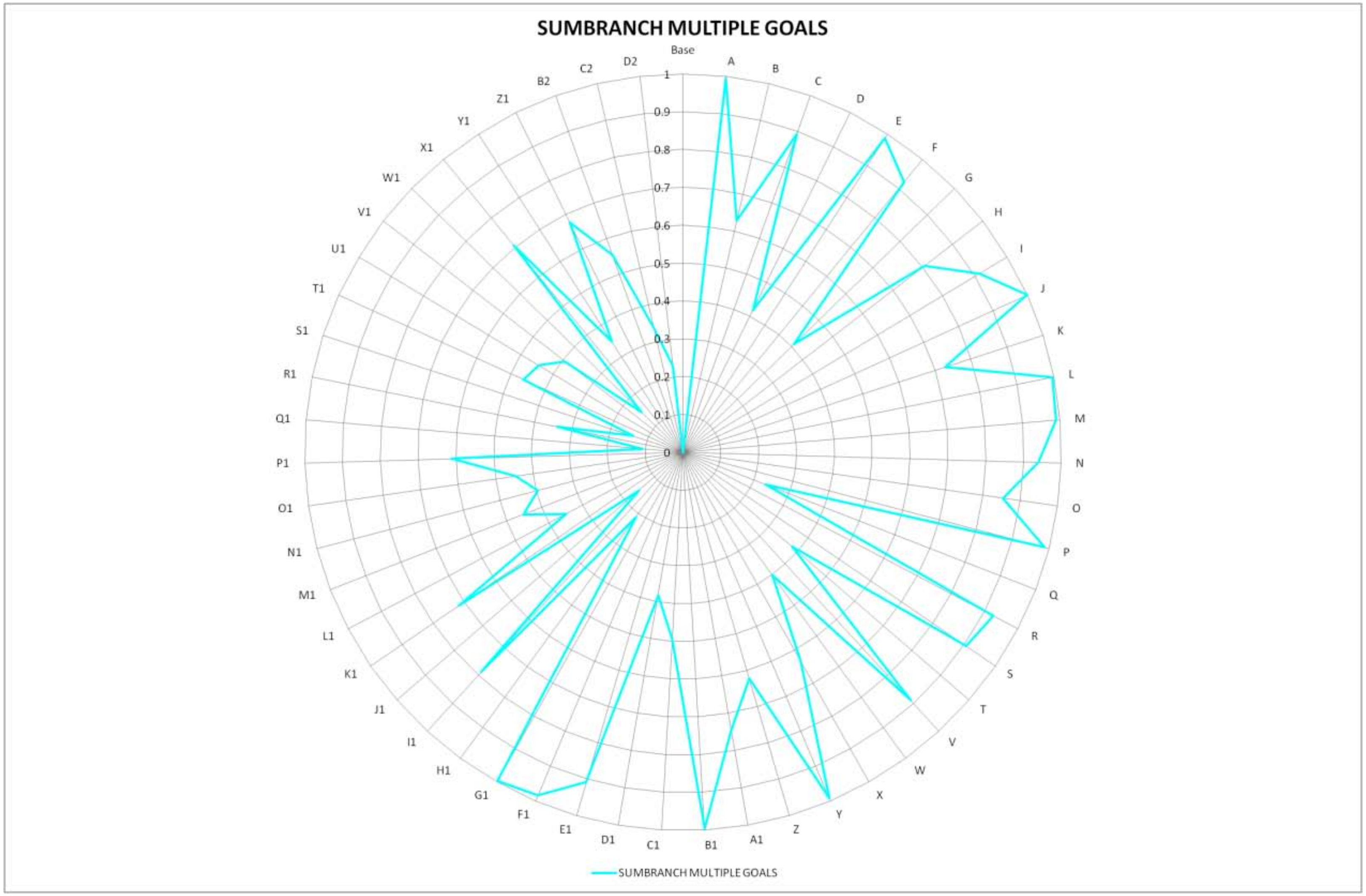


CO_2 Generated



Income

Multiple goals based on Sumbranches



References on Flotation Analysis and Design

•Cisternas. LA., ED. Galvez, MF. Zavala, J. Magna, A MILP model for the design of mineral flotation circuits, *Internacional Journal of Mineral Processing*, 74, 121-131 (2004).

•Cisternas LA., DA. Méndez, ED. Gálvez, and RE. Jorquera, A MILP Model for Design of Flotation Circuits with Bank/Column and Regrind/no regrind selection, International Journal of Mineral Processing, 79, 253-263 (2006).

•Mendez DA., Gálvez ED, Cisternas LA, State of The Art In The Design of Flotation Circuits, International Journal of Mineral Processing (2009).

•Mendez DA., Gálvez ED, Cisternas LA, Modeling of Grinding and Classification Circuits as Applied to the Design of Flotation Processes. Computer & Chemical Engineering, 33 (1), 97-111 (2009)

•Jamett NE, Vielma JP, Cisternas LA, Design of Flotation Circuits Under Uncertainty, Mineral Engineering, submitted (2011)

•Montenegro MR, FD Sepúlveda, ED. Gálvez, LA. Cisternas, Methodology For Process Analysis And Design With Multiple Objectives Under Uncertainty: Application To Flotation Circuits, International Journal of Mineral Procesing, Submitted (2011)

Final Remark

- There are several tools and methodologies for DfS, but they have not been applied to the metal and mining industry.
- Methodologies for design, analysis and optimization must be adapted to metal and mining industry.
- Limited availability of thermodynamic information, the variability and non-homogeneity of ores, particulate process poorly understood are the main challenges to apply PSE methodologies in DfS.
- To date our group has worked on issues such as crystallization, flotation, leaching, solvent extraction and dewatering.


THANK YOU
Grazie
Obrigado
Koszonom
Mahalo
arigato
Спасибо
Takk
Рахмет
Prasom
Gracias
Danke
Dziekuje
Merci
Multumesc