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A cost perspective for long distance ore pipeline water and energy utilization. Part II: Effect of input parameter variability

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ABSTRACT

The simultaneous efficient use of water and energy in long distance hydraulic transport of copper or iron concentrates in dynamic energy and/or water cost scenarios has been recently studied as an optimization problem (Ihle, *Int. J. Miner. Process*, 2012, submitted), including static input parameters of hydraulic interest, such as the specific gravity of solids, slurry particle size distribution and loose packing concentration. It is common that such variables fluctuate throughout the concentrate line operation, and thus the optimal estimated values in the light of the aforementioned optimization model. In the present paper, a continuation of the latter analysis including the effect of input parameter variability by means of a Monte Carlo analysis is proposed. Results show that, under a variety of unit water and energy cost scenarios, lack of process follow-up in front of relatively small variations of input parameters might cause important effects in optimal water and energy consumption, ultimately resulting in increased operational costs. By taking a copper concentrate long distance pipeline example case detailed in Ihle (2013b), present simulations reveal fluctuations on water and energy use close to 8% and 17%, respectively, whereas total costs may have variations up to 18%.

1. Introduction

The hydraulic transport of ores through long distance pipelines, though not belonging in the heart of the mining and mineral processing operations, is among the important energy consumers and greenhouse gas emission agents in large-scale mining plants (Norgate and Haque, 2010; Ihle, 2013a). It is *vox pupuli* in some countries including Chile that the energy and water price and/or scarcity along with increasingly restrictive environmental regulations are questioning the feasibility of ore extraction and beneficiation projects that, perhaps one decade ago, would have had a smooth conception and subsequent startup. This reality suggests that water and energy costs derived from long distance ore pipeline operations may drive a near-future need to optimize operational and infrastructure designs to minimize them. In a companion paper (Ihle, 2013b, named to herein as P1), a scalar function of hydraulic properties and water cost has been derived and, in the absence of input variable uncertainties, a total cost function has been optimized for slurry concentration, total volume flow and pipeline utilization. For the case solved, consisting of copper concentrate flowing in a horizontal, 100 km pipeline, except for low tonnages and comparatively low water costs, optimal solids concentrations were found to be consistently higher than those corresponding to many operations (see P1 for a review). It is known, on the other hand, that input variable uncertainties driving fluctuations of critical parameters such as power consumption, friction losses and water utilization are strong functions of the solids concentration when the latter approaches to the loose packing value (Ihle and Tamburrino, 2012a). The implications of such local variations not only affect economic and social resources such as energy and water, but may also threaten system stability and operability. In large-scale copper or iron concentrate plants, the economic impact of a several-hour system failure is as severe as easy to compute. It is therefore of major importance to commensurate such variations and put them in the context of both system design and operations. In this paper, a Monte Carlo approach is used to assess the impact of random fluctuations of key input variables in the optimal solutions including energy and water cost as proposed in P1.

2. Problem description and solution method

In P1, a set of optimal operational conditions (flow, pipeline utilization and volume concentration) have been found taking into account the effect of water and energy costs in a 100 km, 6 inch nominal copper concentrate pipeline. The optimization problem solved therein —Eq. (4) in P1— is:

$$\Omega = c_W \forall + c_E E, \tag{1}$$

where Ω, the objective function, is expressed in cost units, $\forall$ is the volume of water spent in the pipeline in a certain period of time, E the

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amount of energy required to transport the slurry —not only the dry material—, over the same period, c_W and c_E are unit cost values.

Here, the same rheology, deposit velocity and pressure loss model assumptions than in P1 are assumed. In particular, a Bingham plastic rheology (Ihle and Tamburrino, 2012a,b, and P1), Thomas and Wilson (1987) (also Wilson and Thomas, 1985) model for pressure losses and Poloski et al. (2010) deposit velocity criteria, have been considered. Additionally, random disturbances of the set of input parameters, including characteristic particle sizes, yield stress estimation, solids specific gravity, pipeline roughness and maximum volume fraction have been introduced to obtain overall resulting fluctuations using a Monte Carlo approach. Such perturbed variables were obtained from the result of deviations from prescribed values of the different input parameters as:

$$X = X_\infty(1 + A\vartheta), \tag{2}$$

where X, the input parameter, is expressed as the sum of a base value, X_∞, $A > 0$ is the amplitude of the random disturbance, ϑ, such that $-1 \le \vartheta \le 1$. The random variable ϑ was chosen to follow a uniform random distribution (Matsumoto and Nishimura, 1998). The amplitude A, thus posed, controls the fractional uncertainty related to the variable. Table 1 shows the different choices for the most sensitive input variables. In general, the different parameter variabilities are commensurate with those indicated in Ihle and Tamburrino (2012a) and represent typical —and small— process fluctuations.

Each objective function evaluation requires to solve numerically the referred implicit Wilson–Thomas equation for wall friction, thus requiring some iterations to converge, along with a significant amount of repetitions of the optimization problem to allow for statistically meaningful results. Fig. 1 shows the resulting average of different numbers of instances of the optimization problem and the random fluctuations as described in (2) for some problem variables. From this figure, it is shown that results tend to converge for number of repetitions exceeding about 1000 instances. Because it represents a trade-off between bias and computational effort, for the purposes of the present work, the choice of $N = 2000$ repetitions for each water/energy cost combination —c_W and c_E values, respectively— was considered, getting statistics from N instances of the optimization problem (1), given the inputs and an estimation of the fluctuations of the input parameters, as referred in Table 1. For each (c_W,c_E) couple considered, it was required between 2×10^5 and 4×10^5 evaluations of the objective function (1) to obtain converged values, and reasonably unbiased statistics of optimal values for the solids volume fraction, ϕ, the pipeline fraction utilization λ, the volume flow Q, the required water volume per unit time $\forall$, the hydraulic gradient J (Eq. (8) in P1), the energy requirement E and, ultimately, the cost function Ω.

The present input parameters are in the order of those found in copper concentrates. However, as discussed in P1, there is a clear similarity and applicability of present computations to iron concentrates, despite the distinctly different typical system tonnages of the latter. To assess present results in the context of a fluctuation metric, a dimensionless variability parameter is defined the same way as the coefficient of variation (Bannerjee, 2008):

$$r_{X^*} = 100 \times \frac{\sigma_{X^*}}{\langle X^* \rangle}, \tag{3}$$

where $\langle \cdot \rangle$ and $\sigma_{(\cdot)}$ represent the average and standard deviation of the series of N runs —normalized by $N-1$— of the optimization problem with differing random input parameters as indicated in (2), respectively. The asterisks represent computed optimal values of the output variable X, that may be ϕ, λ, Q, or an intermediate variable, such as the hydraulic gradient, J.

Table 1
Assumed input variables subject to random disturbances and randomness parameters. The detail of inputs and computation assumptions for the base case is given in Table 1 in P1.

Name	Description	X_∞	A
L	Pipeline length	100 km	0
D	Pipeline inner diameter (6 inch nominal)	146.3 mm	0
$\dot{m}$	Pipeline throughput range (dry)	15.85–39.63 kg/s	0
d_{50}	Median particle diameter	30×10^{-6} m	0.1
d_{RR}	Rosin–Rammler parameter (Eq. (1) in P1)	43.3×10^{-6} m	0.1
m^*	Empirical parameter for yield stress model (Eq. (3) in P1)	0.55	0.2
S	Solids specific gravity	4.2	0.025
ϵ	Pipeline roughness	40×10^{-6} m	0.05
ϕ_m	Maximum volume fraction viscosity model (Eq. (9) in P1)	0.465	0.035

3. Results and discussion

The effect of the input parameter variability has been assessed through the Monte Carlo approach described above. Fig. 2 shows the computed values of the parameter r, as in (3), for the different process parameters.

Fig. 2 shows computed variabilities for 0.5 Mton/year, 1 Mton/year and 1.25 Mton/year, respectively, for different water and energy values. In general, trends in variabilities of input and intermediate parameters such as concentration, pipeline utilization, volume flow and hydraulic gradient, are observed to show strongly nonlinear and non-monotonical behavior, with distinct local minima and/or maxima, depending on the relative sensitivity of the various input parameters to changes in water costs.

It is observed that, for the low-tonnage case ($\dot{m} = 0.5$ Mton/year), a marked local minimum in the concentration and pipeline utilization appears at a water cost close to 1 USD/m^3, as detailed in the inset of Fig. 2a. Although not shown in a separate figure as in Fig. 2a, such local minima are found in optimal pipeline utilizations, λ^*, as well (Fig. 2b). These local extrema are observed, for the same water cost value, as maximal values in the flow and hydraulic gradient curves (Fig. 2c,d). Such low-cost/low-tonnage behavior, previously identified in P1, has been explained as the combined effect of using the pipeline at partial capacity and the predominance of the deposit velocity over the laminar-turbulent transition condition in the minimum velocity selection while minimizing (1). The effect of an increase in system utilization —i.e., λ increasing towards its maximum possible value— or, equivalently, increasing water cost within the low cost range, is to decrease variability in both concentration and system utilization and, likewise, increasing flow and hydraulic gradient. For each water cost range, given fixed values of the energy unit cost, the local rate of change in (3), dr_X/dc_W, may be expressed as:

$$\frac{dr_{X^*}}{dc_W} = \frac{1}{\langle X^* \rangle}\left(\frac{d\sigma_{X^*}}{dc_W} - \frac{\sigma_{X^*}}{\langle X^* \rangle}\frac{d\langle X^* \rangle}{dc_W}\right). \tag{4}$$

Given the present set of hypotheses, including tonnage, unit cost ranges and, importantly, pipeline inner diameter and length as controlling geometrical parameters, the decreasing portion of the low water cost regime found for $\dot{m} = 0.5$ Mton/year corresponds to the case when the right hand side of this expression is negative. Given that in this regime a variable increase (or decrease), is roughly linear, the condition to get the increasing–decreasing transition (or *vice-versa*), is $\sigma_{X^*,c} \approx \sigma_{X^*0}\left(\frac{kc_W+a}{kc_{W0}+a}\right)$, where a, k and c_{W0} are constants. This behavior is interpreted in the light of the relative increase (or decrease) of the optimal average variables in the different regimes. While in the low water cost regime, all variables (concentration, pipeline utilization, etc.) increase and decrease linearly and strongly (Fig. 4 in P1), their growth exceeds that of the standard deviation, represented by σ_{X^*}, explaining the decreasing portion of the variability curves. On the other hand, for relatively higher throughputs and/or water costs, average variables experiment a much milder growth (or decrease), thus