Comminution process optimisation through reliability and maintainability modelling and simulation

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ABSTRACT

The mineral processing industry is characterised for its intense use of fixed assets; therefore the careful management of these assets, from the inception of a new investment project to the completion of its operational life, is fundamental to attain positive business results. In this context, operational reliability becomes a relevant variable for optimising projects in their design phase, allowing critical elements that could affect the runtime of the process to be identified and opportunities for saving on capital expense to be determined.

The objective of this paper is to develop a methodology, using RAM[1] modelling and a simulation of the processes to enable projects to be appraised and optimised in their feasibility study phase. Thus, a Life Cycle Cost approach will be used to evaluate the effect of changes on the flow sheet and the capacity of equipment and stockpile systems in order to assess the business impact of proposed modifications and select the best combination, taking into account expected production and required investment.

The methodology will be validated in a comminution plant utilising information of similar real life operations. As a result of the application, it will be possible to determine an improved scenario with an estimated net benefit achieved through modifying the base case. The use of reliability engineering software is proposed as a platform to model processes and equipment fault behaviour in order to determine, through stochastic algorithms, the availability and risk associated with each scenario.

Finally, the main results and conclusions will describe the potential of the methodology, showing solid results in terms of savings obtained through its application, with net increases in NPV of up to US$1.6 billion, including US$117m from decreased CAPEX and US$1.4b from increased production over the life cycle of the project.

[1] Reliability, availability and maintainability

INTRODUCTION

'Modelling a complex system by using RBDs (Reliability Block Diagrams) (Levitin, 2007) is a well known method adopted for reliability' (Macchi et al., 2010), availability and maintainability analyses, known as RAM modelling and simulation (Arata, 2009). 'A RBD is built after logical decomposition of a system into its subsystems. Further on, the RBD is drawn out to express, in a network of subsystems' (Macchi et al., 2010), reliability logic stages such as series, parallel or k/n (total or partial redundancy), standby and shared load (fractionation). 'By means of this logic, a complex production system can also be analysed: the subsystems are combined in order to model the real production system and analyse the effects of a failure occurring in a subsystem (e.g. a subset of machines) at the global system level' (Macchi et al., 2010; Arata, & Furlanetto, 2005).

'RBD logic is used for different applications in system reliability analysis and, moreover, they are supported by software. In this respect, RBD can be considered a modelling tool which is consolidated and available at hand for the normal duties of reliability and maintainability analysis. Indeed, process engineers may adopt RBDs; at least, in order to make a logical, qualitative analysis of the functional relationships that exist between components of a whole system; at most, they may use RBDs to make the quantitative assessment of the properties of the whole system'(Macchi et al., 2010), such as its availability or the runtime that can be expected at the system or subsystem level over the life of the project.

Also, with an adapted RBD approach it is possible to consider, through a Monte Carlo simulation, the effect on the process of a stockpile system (Macchi et al., 2010; Heidke, 2010). In fact, buffers are capable of providing continuity between two stages of the process thanks to the accumulation of production material they allow. Within the buffer, the inventory is accumulated from the upstream subsystem and released to the subsystem downstream. As a result, the buffer inventory level plays a relevant role on the propagation of the effect of a failure along the entire system. Indeed, a proper amount of inventory could prevent any propagation by guaranteeing the isolation time needed to recover from failure of the upstream subsystem, without causing production losses downstream (thus avoiding 'material starvation'). Conversely, it can guarantee the isolation time needed to recover from failure of the downstream subsystem, without causing production losses upstream (thus avoiding 'blocking of production').

Hence, through RBD modelling, using the Reliability and Maintainability Engineering System (R-MES) Platform, which considers the presence of stockpile systems, and the subsequent RAM simulation, the process runtime can be determined, based on the historical performance of equipment detentions. Therefore, the results obtained from multiple repetitions that provide a probability distribution of the runtime and therefore of the production of the process, shall be used later on in the economic evaluation of the different alternatives in designing the process. Finally, once the impact on the production levels of the base cases is established for each of the improvement options, it is possible, with the help of optimisation software, to select the best economic alternative. The assessment is based on increasing (or decreasing) the CAPEX, provided that the higher (or lower) equipment capacity, idle capacity or stockpile capacity, compensates variations in the production level.

This approach is valuable in that it allows the life cycle profitability and risk associated with different scenarios formed by a combination of improvement opportunities in each process to be determined. Thus, it is possible to maximise the NPV of the project on the basis of its expected runtime, investment and particular contractions, such as budget or risk (given the probability of runtime being lower than a given value).

METHODOLOGY

The methodology consists of five principal stages:

- *Process understanding:* consists of establishing and understanding the project with the purpose of obtaining the necessary information for the RBD modelling of processes. This stage considers the assessment of design criteria, equipment capacities and operation criteria.

- *Data base consolidation*: this is where the database consolidates the hold-ups of equipment resulting from planned maintenance, unplanned maintenance and operational shutdowns by gathering the historical information generated on equivalent projects in the operation and the maintenance schedule for the project. In terms of unplanned maintenance, the information regarding the time between failures (reliability) and the time to repair (maintainability) is used to obtain the best fit of the fault behaviour of each piece of equipment.

- *RBD modelling:* consists of reliability block diagramming which defines, through a logical-functional approach, the impact on the overall system due to the shut-down of each piece of equipment. Thus, the relationship between pieces of equipment or subsystems could be serial, parallel, stand-by, k/n or shared load. Also at this stage the stockpile systems downstream of each process are modelled.

- *RAM simulation and analysis:* consists of a Monte Carlo simulation to both determine the expected availability and runtime of the base project and to identify improvement opportunities. Also at this stage, each of the potential improvements is evaluated, through a new RAM simulation, in terms of its marginal effect over the plant runtime. This is done in order to evaluate the expected production for different scenarios and to determine the response against a number of variables. Listed below are the main activities carried out at this stage:

  a. Determining RAM indicators at equipment, process and system levels (availability, reliability (mean time between failure, MTBF) and maintainability (mean time to repair, MTTR)).
  b. Determining performance indicators at equipment, process and system levels (utilization, runtime, expected production).
  c. Identifying bottlenecks and critical equipment/processes.
  d. Determining the effects of changes in reliability and maintainability (+/- MTBF, +/- MTTR).
  e. Quantifying the contribution of stock-pile units to system reliability.
  f. Analysing risk and the probability of reaching specific production levels.
  g. Identifying potential opportunities for improvement to be evaluated: a) changes in equipment capacity, b) changes in the logical configuration of the system (share load, parallel, k/n, stand-by), c) changes in the capacity of stock-pile, d) incorporation/removal of equipment, e) other changes in the process such as a by-pass flow.

- *LCC valuation and optimisation:* consists of the economic valuation of different scenarios with the purpose of identifying, through *operations research software*, the scenario or combination of improvement opportunities that maximise the net present value (NPV) over the life cycle of the project. The importance of this stage is that the optimal alternative would not incorporate all the improvements, because each of them represents not only a change in the expected runtime but also an increase or decrease in capex. In addition, determining the best scenario will depend also on the scaling factor in the cost of equipment, the projected price of copper concentrate and any particular restrictions in the project, such as the investment budget.

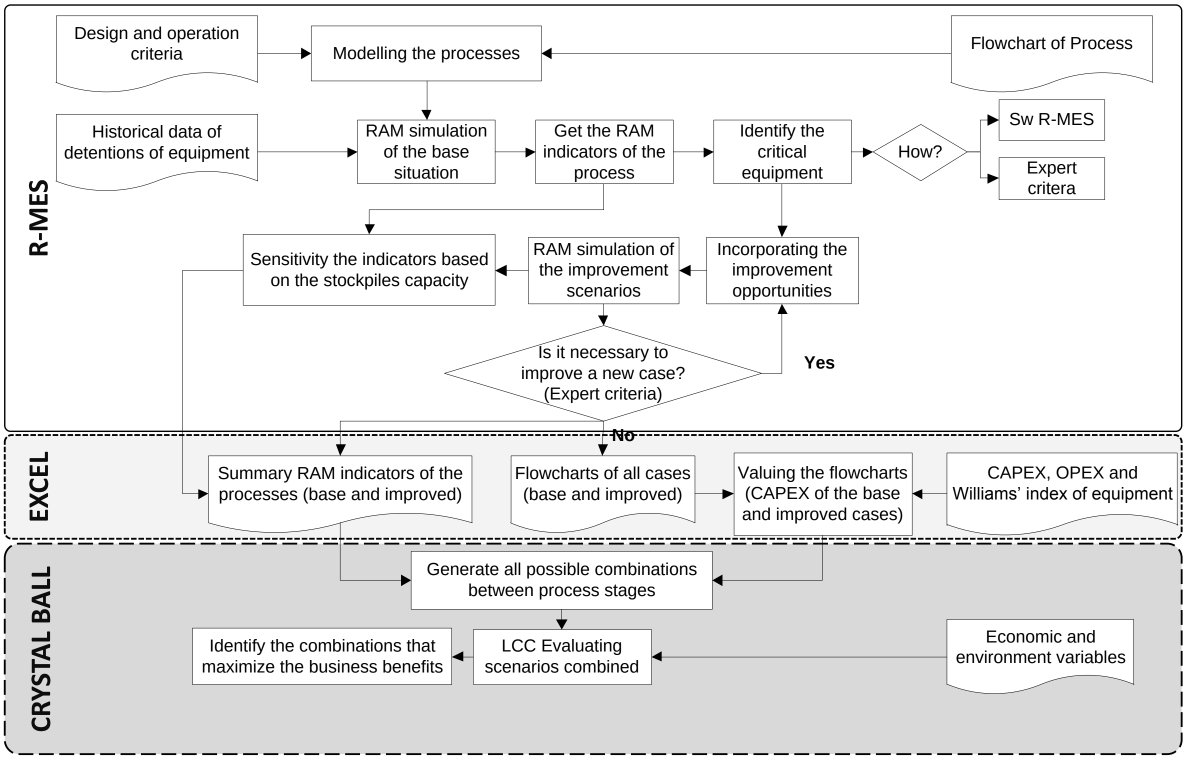


Figure 1 Flowchart of simulation and optimisation methodology to approach the project

DEVELOPMENT

The following description explains the development of the different project stages with regards to the aforementioned methodology. However, in order to summarise this presentation, some analyses will be omitted and certain issues will be covered, showing only a few cases as examples.

Project understanding

The project consists of a comminution process of pre-feasibility engineering that is equipped with installed capacity of 191 520 tonnes per day (tdp) of mineral ore to reach an average production level of 180 000 tpd.

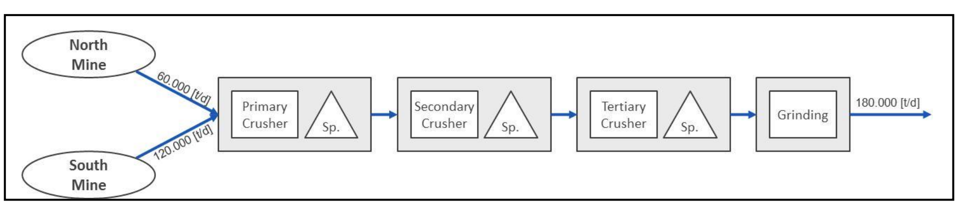
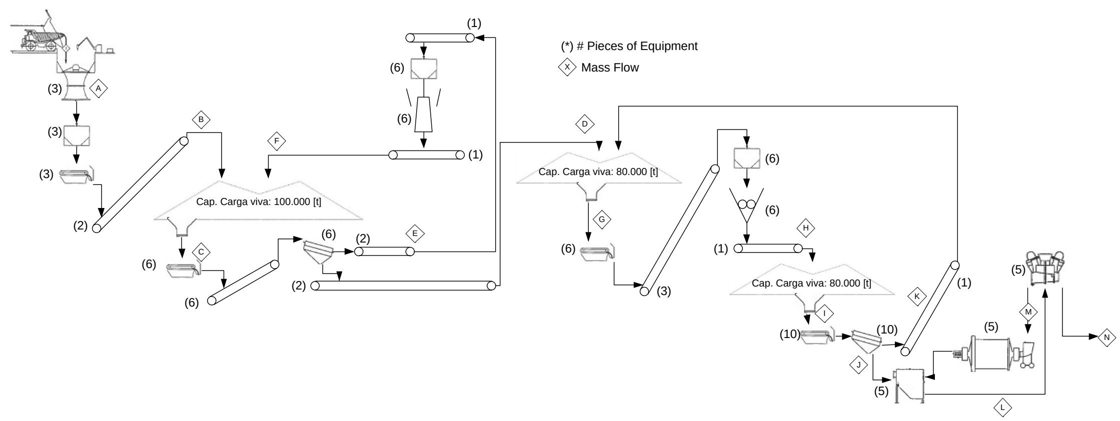


Figure 2 Structure of the process under study

The project to be evaluated consists of three crusher stages (primary, secondary and tertiary) and one grinding stage, and is fed by copper ore originating from two mines, one of them called Mina-Norte (MN), with an average extraction of 60 000 tpd, and the other Mina-Sur (MS), with an average extraction of 120 000 tdp. The process flowsheet diagram appears in the following figure.



		Primary Crusher Feed	Primary Stockpile Feed From Pri. Cr.	Secondary Crusher Lines Feed	Undersize material	Oversize Material	Primary Stockpile Feed From Sec. Cr.	Tertiaty Crusher Feed	Terciary Stockpile Feed From Ter. Cr.	Grinding Lines Feed	Undersize Material	Oversize Material	Hydrocyclon Feed	Ball Mill Feed	Troughput of process
		A	B	C	D	E	F	G	H	I	J	K	L	M	N
Nominal Flow	[t/h]	7,500	7,500	11,111	7,500	3,611	3,750	11,720	11,720	11,720	7,500	4,220	30,000	22,500	7,500
Designg Flow	[t/h]	10,714	10,714	13,072	8,824	4,248	4,412	12,739	12,739	12,468	7,979	4,489	31,915	23,936	7,979

Figure 3 Flow chart of the process under study

Data base consolidation

In order to make up the database, information was used from five mining operations (74 pieces of equipment) consisting of a total of 8732 records divided into operational hold-ups (DO), planned maintenance (MP) and unplanned maintenance (MC), which could be mechanical (MCM), electrical (MCE) or related to instrumentation (MCI). The information is consolidated into the following format as a base for the R-MES simulation.

Table 1 Standard format for importing data into R-MES

Date	Time [hr]	Duration [hr]	Type	Equipment
01-01-2010	11:38	5.35	MCM	EQUIPMENT-1
01-01-2010	11:45	4.2	DO	EQUIPMENT-2
06-01-2010	6:18	40.6	MP	EQUIPMENT-3

RBD modelling

RBD modelling is performed on the R-MES Platform through the logical-functional configuration between equipment and systems (series, parallel, stand-by, k/n and fractionation or sharing load). Through this procedure, it is possible to determine the impact on the process of the hold-up of a piece of equipment. The following shows an RBD diagramming scheme for one of the processes.

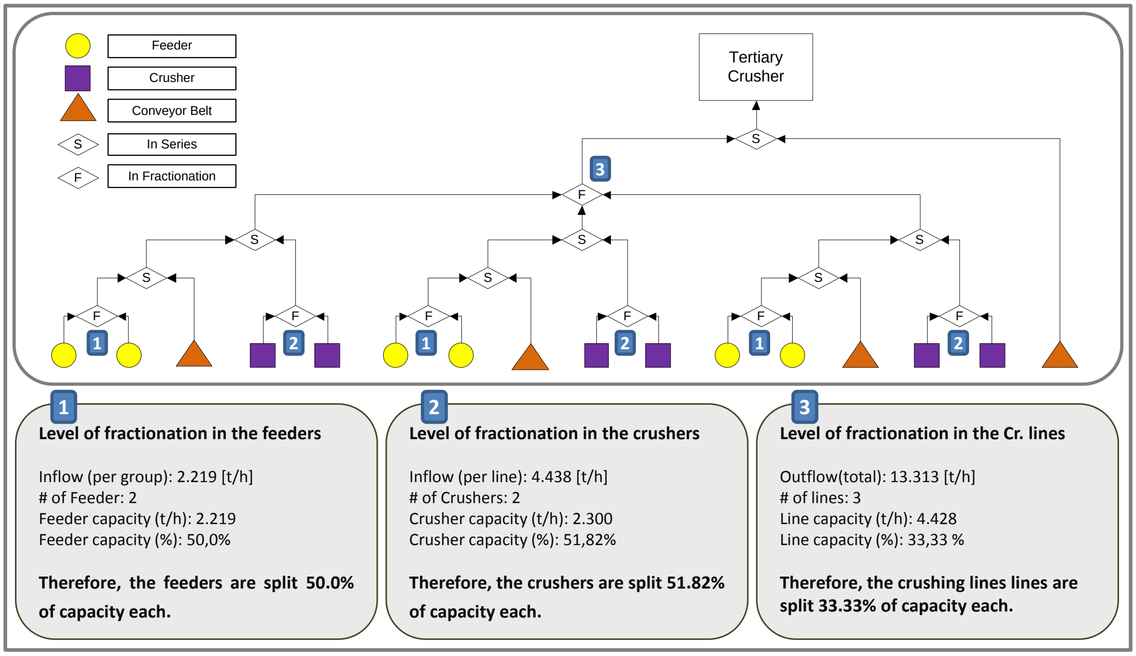


Figure 4 Logic-functional diagram of the tertiary crusher

RAM simulation and analysis

The RAM analysis of the different scenarios is made through the Monte Carlo simulation, and it also obtains the variance of availability and runtime, based on the distribution of the probability of the entry variables, such as time to repair, time between hold-ups and time between maintenance. Thus, the impact on the production level is quantified as a result of modifying the capacity of pieces of equipment or stockpile systems. The following shows a histogram that represents the expected availability for tertiary crushing.

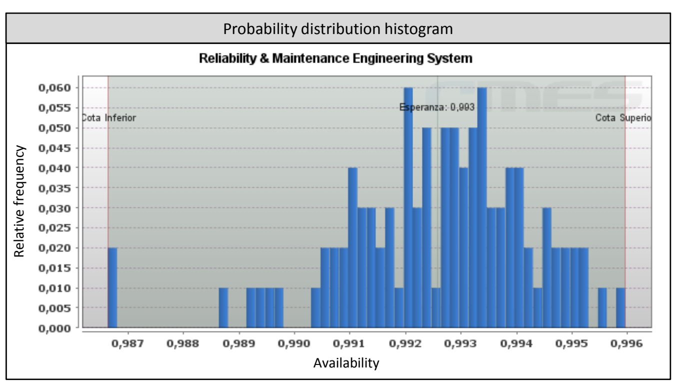


Figure 5 Simulation results for the availability of tertiary crushing

The following figure shows the sensitivity of the availability of the 'tertiary crushing + stockpiling' process in terms of stockpile live capacity upstream. Observe that as from 10 000 tonnes, there is practically no increase in the availability of the process.

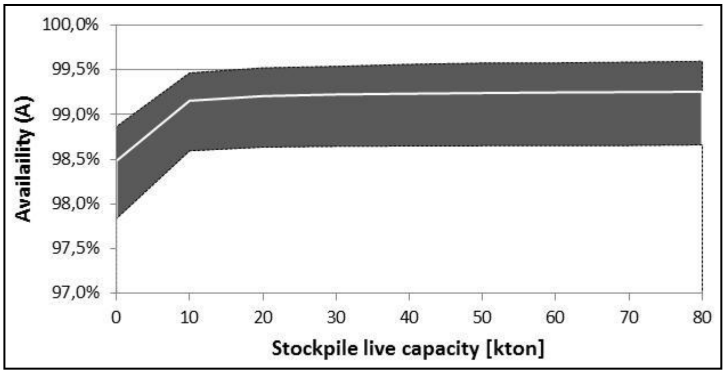


Figure 6 Sensitivity of availability of tertiary crusher against downstream stockpile capacity

The following figure shows a summary of the results of usage and availability for the different tertiary crushing alternatives. The base case and three improvements identified through critical analysis are considered. This methodology is replicated for the different processes that make up this project.

Base Situation	Improvement 1	Improvement 2	Improvement 3
-	Incorporation of idle capacity in the HPGR crusher, from 51.82% to 65% each.	Incorporation of a conveyor belt to the discharge of material over the downstream stockpile, parallel to the existing one.	Improvement 2 & 3.

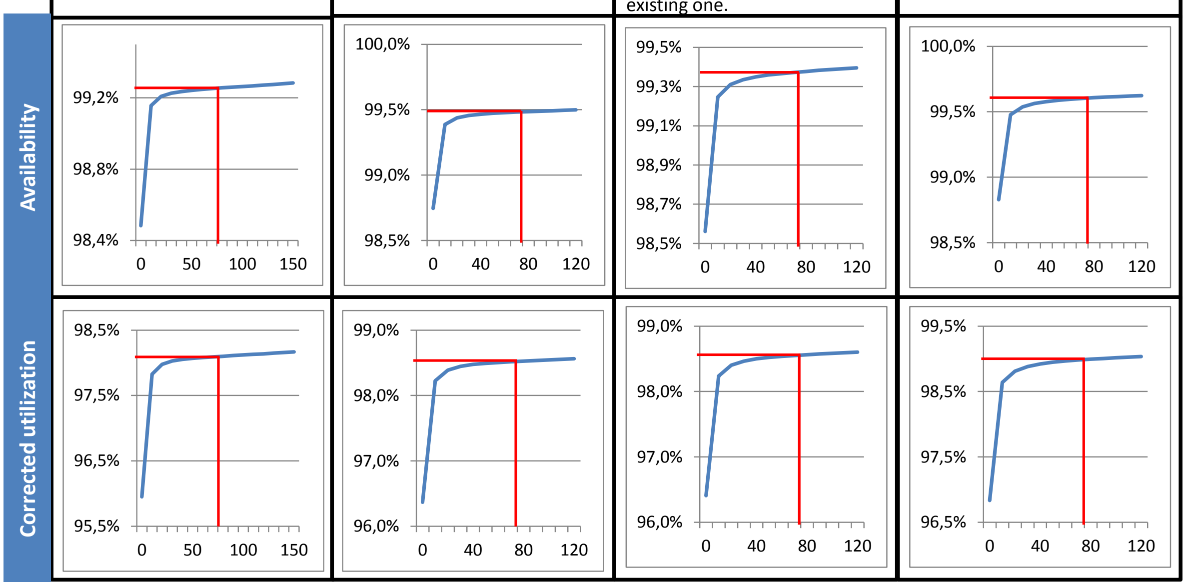


Figure 7 KPI summary of tertiary crusher

LCC valuation and optimisation

At this stage an economic assessment was made of each process and its different alternatives. The Williams scaling factor was used to determine the change in CAPEX by modifying the capacity of the pieces of equipment with respect to the value defined in the base case. Furthermore, estimates were made of working capital, operational costs (OPEX) and income based on the expected runtime in each case and the price of copper concentrate. The LCC valuation was used to begin an iteration process designed to identify the combination of cases which maximise the NPV of the project under a given budgetary restriction and probability of occurrence.

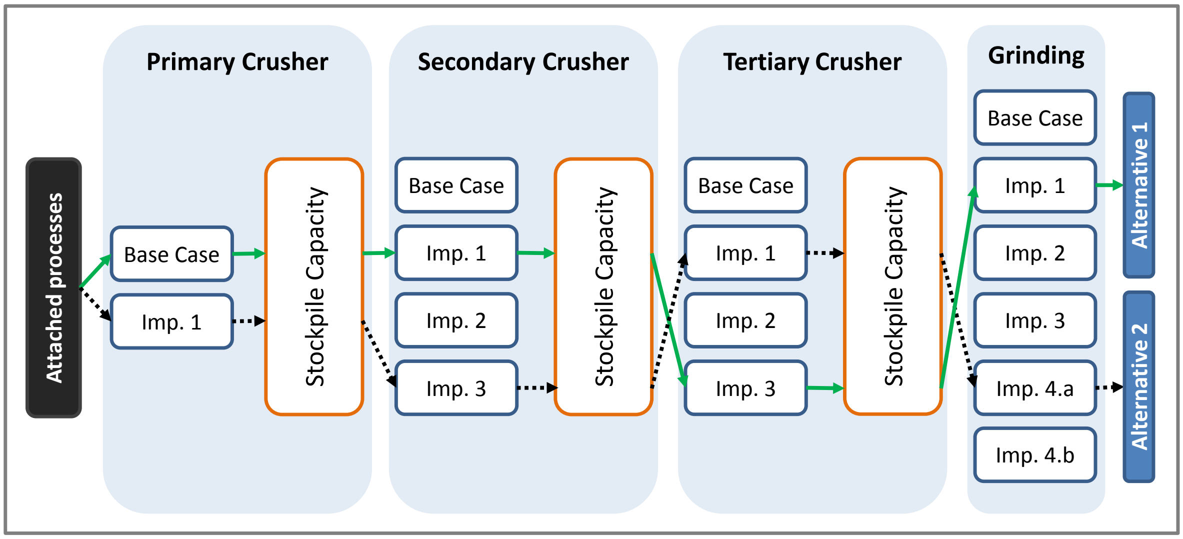


Figure 8 Outlining the selection of alternatives for LCC evaluation

MAIN RESULTS

A total of 475 200 scenarios were evaluated and the following table shows the combination of improvements that maximise NPV at different prices of copper concentrate.

Table 2 Summary of optimal scenarios for each environment

Price of Cu conc.	1,5 [US$/lb]		2,0 [US$/lb]		2,5 [US$/lb]		2,5 [US$/lb] *		3,0 [US$/lb]		3,4 [US$/lb]		4,0 [US$/lb]	
Processes	*Scenario*	*Stockpile Capacity*	*Scenario*	*Stockpile Capacity*	*Scenario*	*Stockpile Capacity*	*Scenario*	*Stockpile Capacity*	*Scenario*	*Stockpile Capacity*	*Scenario*	*Stockpile Capacity*	*Scenario*	*Stockpile Capacity*
Primary Cr.	Base	50.000	Base	50.000	Base	50.000	Base	50.000	Imp. 1	50.000	Imp. 1	50.000	Imp. 1	50.000
Secondary Cr.	Imp. 3	10.000	Imp. 3	10.000	Imp. 3	20.000	Imp. 3	10.000	Imp. 3	20.000	Imp. 3	40.000	Imp. 3	40.000
Tertiary Cr.	Base	10.000	Base	10.000	Base	10.000	Imp. 2	20.000	Base	10.000	Base	10.000	Base	10.000
Grinding	Imp. 4.b	-	Imp. 4.b	-	Imp. 4.b	-	Imp. 4.a	-	Imp. 4.b	-	Imp. 4.b	-	Imp. 4.b	-

(*) Optimal scenario, considering that the savings in CAPEX must be at least US$120 000 000

The following table shows the NPV for the optimum scenario for the different copper concentrate prices. It also indicates the increase in NPV for each scenario in comparison with the base case.

Table 3 Summary Results of the LCC evaluation

		Optimized Cases				Base Cases				
Price of Cu. Concentrate	Systemic Corrected Utilization	CAPEX [bUS$]	OPEX [bUS$]	Annual estimated sales [bUS$]	NPV [bUS$]	Annual estimated sales [bUS$]	NPV [bUS$]	NPV increase over the base case	CAPEX decrease of project over the base case	Cash flows increase over the base case (in present value)
1,5 [US$/lb]	91,75%	$ 1,98	$ 0,67	$ 1,23	-$ 0,18	$ 1,09	-$ 1,05	**$ 0,87**	**$ 0,13**	**$ 0,74**
2,0 [US$/lb]	91,75%	$ 1,98	$ 0,67	$ 1,64	$ 2,81	$ 1,45	$ 1,60	**$ 1,21**	**$ 0,13**	**$ 1,08**
2,5 [US$/lb]	92,00%	$ 1,99	$ 0,67	$ 2,06	$ 5,81	$ 1,82	$ 4,25	**$ 1,56**	**$ 0,12**	**$ 1,45**
2,5 [US$/lb] *	90,91%	$ 1,98	$ 0,66	$ 2,03	$ 5,68	$ 1,82	$ 4,25	**$ 1,43**	**$ 0,12**	**$ 1,31**
3,0 [US$/lb]	92,11%	$ 2,00	$ 0,67	$ 2,47	$ 8,80	$ 2,18	$ 6,89	**$ 1,91**	**$ 0,11**	**$ 1,80**
3,4 [US$/lb]	92,33%	$ 2,02	$ 0,67	$ 2,81	$ 11,21	$ 2,47	$ 9,01	**$ 2,20**	**$ 0,09**	**$ 2,11**
4,0 [US$/lb]	92,33%	$ 2,02	$ 0,67	$ 3,30	$ 14,81	$ 2,91	$ 12,19	**$ 2,62**	**$ 0,09**	**$ 2,54**

(*) Optimal scenario, considering that the savings in CAPEX must be at least US$ 120,000,000

CONCLUSION

This paper proposes a methodology for optimising processes through reliability engineering using a LCC (Life Cycle Cost) perspective, which enables the effect on expected production of a change in the processes reliability to be quantified and the best combination of improvements considering the increase or decrease in capex involved in each new scenario to be determined. Thus it incorporates a new decision variable to enable the profitability of a new investment project to be maximised. In this case in particular, for an assumed copper concentrate price of US$2.5/lb, the methodology enables net increases in NPV of up to US$1.6 billion, including US$117 million due to decreased CAPEX and US$1.4 billion due to increased production over the life of the project, estimated at 25 years.

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