

Enhancement of Profitability of Central African Copperbelt Operations using Direct Cobalt Electrowinning Process

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Direct cobalt electrowinning was developed to produce unrefined cobalt metal as an alternative to producing a mixed hydroxide product (MHP), which is the common cobalt intermediate product in African Copperbelt operations. MHP is preferred due to the high cost of producing high-grade cobalt cathode. Direct cobalt electrowinning test work results have shown that the purity of the unrefined cobalt metal produced from a low-grade copper solvent-extraction raffinate stream was ~97% (w/w), which is significantly higher than the MHP purity (up to 45% (w/w) Co).

The current study investigates whether direct cobalt electrowinning would increase the profitability of African Copperbelt copper-cobalt oxide operations, when compared with the MHP flowsheet. An order-of-magnitude economic evaluation was conducted using dynamic differential discounted cash flow models on a “bare-bones” basis, using a 10% discount rate. Three variables were evaluated, namely; reagent utilisation extents, precipitation extents and filter-press wash efficiency. Multivariable risk analysis was also conducted using the Monte Carlo simulation technique to understand the impact of key project drivers.

The financial study results indicated that a direct cobalt electrowinning flowsheet could potentially result in a higher mean net present value (NPV) compared with the MHP flowsheet. Cobalt recovery was found to have the most significant impact on the NPV. In addition to increased profitability of African Copperbelt operations, direct cobalt electrowinning has the potential to reduce the environmental footprint of operations as well as addressing the Democratic Republic of Congo government’s drive towards export of higher value metal products instead of low-grade intermediates.

INTRODUCTION

The African Copper-belt contains the largest cobalt (Co) reserves, estimated at 45% of the world’s reserves (Bedder, 2013). The Kolwezi Klippe (Kamoto-KOV-Musonoi-Mupine) deposit in the Katanga province of the Democratic Republic of the Congo (DRC) is considered the world’s largest known resource of Co (Taylor et al., 2010). The Cu and Co grades in this deposit are estimated at 4.49% and 0.39%, respectively. The Co grade in the Copperbelt varies across the different deposits within the region, with grades generally between 0.17% and 0.25% Co (Hannis & Bide, 2009); however, there are deposits known to have higher Co grades.

There has been an increase in Co output from the DRC due to the high demand resulting from the rechargeable battery and superalloy markets (Minor Metals Trade Association, 2015). As a result, the value of Co products has increased, with the London Metal Exchange (LME) Co price (US\$ 29 900/t) currently five times that of the LME Cu price (US\$ 6 090/t) (LME Cobalt, 2015; LME Copper, 2015). The high Co demand has also led to significant developments in the hydrometallurgical processing of Co from the African Copperbelt, and Mintek has been a major contributor to feasibility studies aimed at flowsheet design and optimisation for several African Copperbelt operations.

The traditional Cu-Co flowsheet typically recovers Cu and Co from the ore by reductive leaching with sulphuric acid, followed by Cu recovery using solvent extraction (CuSX) and electrowinning (CuEW). The high-grade raffinate from the CuSX circuit is returned to the leach for water balance purposes and to provide sulphuric acid for Cu-Co recovery. The low-grade CuSX raffinate serves as a bleed stream and is necessary to control the levels of impurities in the CuSX-EW circuit. This stream is the feed to the Co recovery circuit. Depending on the Co grade in the ore, Co price and the cost of producing the Co by-product, Cu producers may opt to neutralise the entire CuSX raffinate bleed stream and discard the residue in a tailings dam. The Co flowsheet is determined by the choice of the Co product (Fisher, 2011). There are typically three saleable Co products, namely (Swartz et al., 2009):

- Cobalt concentrate using gravity separation;
- Cobalt intermediates – mixed sulphides, hydroxides or carbonates;
- Cobalt metal – high grade (HG) (99.8% Co) or low grade (LG) (99.3% Co).

The value of the Co product increases as the level of refining increases; however, this is accompanied by a proportional increase in capital and operating costs (Swartz et al., 2009). A KPMG 2012 report on the DRC revealed that only 5% of the exported Co was refined, with the remainder being Co concentrate and intermediate product, which is usually a mixed hydroxide precipitate (MHP) (Parant et al., 2013). This trend is expected to continue in the medium term due to the complexity and high cost of producing high-grade Co metal in the DRC (Swartz et al., 2009; Pawlik & Lydall, 2012).

The DRC government has, in recent years, made efforts to promote the expansion of exporting domestically value-added products in order to increase revenue collection from the country's major resource (Bedder, 2013). A ban on the export of Cu and Co ores, and their concentrates, was announced in May 2013; although the ban was not enforced, it does give an indication that government could take action in future (Roskill, 2014). In addition, the DRC government increased export tax from US\$ 60/t to US\$ 100/t, which should encourage Co producers to export higher value products to minimise the impact of export taxes on Co revenue and profitability.

Given the abovementioned challenges, the majority of Co producers opt for an MHP intermediate product using MgO, to obtain a higher purity (up to 45% Co (w/w)) product as compared with the products obtained when using lime or limestone (<20% Co, (w/w)) (Fisher, 2011). However, MgO is an expensive reagent, and availability of MgO is a concern due to a long logistical chain for supply of reagents to site, which also results in a large carbon footprint because MgO is usually imported from the United States of America (USA) or Australia (Fisher, 2011). This problem is compounded by poor transport infrastructure and consequently high transport costs (Parant et al., 2014).

In view of the aforementioned factors, Mintek has investigated the possibility of an alternative high-quality Co product, derived from the CuSX raffinate bleed at reduced operating costs, in order to enhance the process economics of the Cu-Co flowsheet. This alternative flowsheet would have the following advantages compared to the MHP circuit:

- Co metal of high grade, although not LME grade, hence potential for higher Co revenue;
- Elimination of MgO, hence minimising the impact of logistics on process operations;

- Lower operating expenditure (OPEX) due to elimination of MgO, and reduced Co product transport costs and export taxes.

Based on these potential economic benefits, Mintek undertook laboratory test work to determine the operating conditions for direct cobalt electrowinning (CoEW) and also conducted mass balances were to compare reagent costs and Co revenue for the MHP and direct CoEW flowsheets. A patent for the direct CoEW technology was granted in 2012 (Kotze & Tripathy, 2012). Therefore, Mintek conducted an Order-of-Magnitude (OoM) desktop study in collaboration with DRA Mineral Projects in order to determine the capital expenditure (CAPEX) and operating expenditure (OPEX) estimates for the direct CoEW flowsheet relative to the MHP flowsheet, and the results are discussed in this paper.

BACKGROUND

Direct Co Electrowinning Test Work

Mintek has conducted extensive laboratory test work on the electrowinning (4 L cell) of Co from the CuSX raffinate bleed stream after Fe, Mn and Al removal. Test work conditions and results were discussed in detail by Mulaudzi & Kotze (2013). Test work was aimed at evaluating the process performance, given the dilute Co concentration and higher impurity levels in the CuSX raffinate when compared with conventional CoEW electrolytes. Hence, the CoEW current efficiency was expected to be lower, which means that the cell-house size would be significantly larger compared with that of conventional CoEW. The range of operating parameters for direct CoEW determined from the test work results, are shown in Table I.

Table I. Direct CoEW operating conditions.

Parameter	Value
Current density (A/m ²)	125 - 150
Cell voltage (V)	4 - 5
Current efficiency (%)	30 - 40
Power consumption (kWh/kg Co)	10 - 12
Delta Co (g/L)	2
Spent electrolyte pH	1.5

Flowsheet Comparison

The Co flowsheet, producing either MHP or Co metal, was compared with a basic African Copperbelt flowsheet without Co recovery (Figure 1), which was considered to be the base case for the economic evaluation. The selected Co flowsheet producing high quality MHP is shown in Figure 2, where Co was precipitated using MgO from the raffinate bleed after Fe, Al and Mn removal. Fe and Mn were removed by oxidative precipitation using an air/SO₂ gas mixture, in conjunction with limestone to maintain the solution at pH 3.5.

Al was precipitated using lime at pH 4 to 4.5. The Fe/Mn/Al thickener overflow would be sent to the primary Co precipitation step. Co was recovered with MgO at an 80% Co precipitation extent in the first Co removal stage, which would typically be operated at pH 6.5 to pH 7. The remainder of the Co is precipitated using lime in the second stage of the Co precipitation circuit, which would be operated at pH 7 to 8. The second-stage Co precipitate was recycled to Fe/Mn/Al precipitation for re-dissolution. Mg was precipitated from the Co precipitation barren solution to prevent Mg build-up in the circuit.

The direct CoEW flowsheet was derived from the MHP flowsheet and is shown in Figure 3. A Cu polishing step, using a small secondary SX circuit, was included in this flowsheet in order to reduce the Cu concentration in the feed to CoEW to the desired tenor.

The CoEW step replaced the two Co precipitation stages; thus eliminating the Mg precipitation stage and the lime associated with Mg precipitation. The CoEW spent electrolyte was split; a fraction was precipitated with lime and recycled to Fe/Mn/Al precipitation to build-up the Co tenor feeding CoEW. The remainder of the CoEW spent electrolyte was recycled to the upfront circuit for water-balance purposes, to maintain a high Co tenor to the Co circuit and to reduce the fresh acid requirement in the leach circuit.

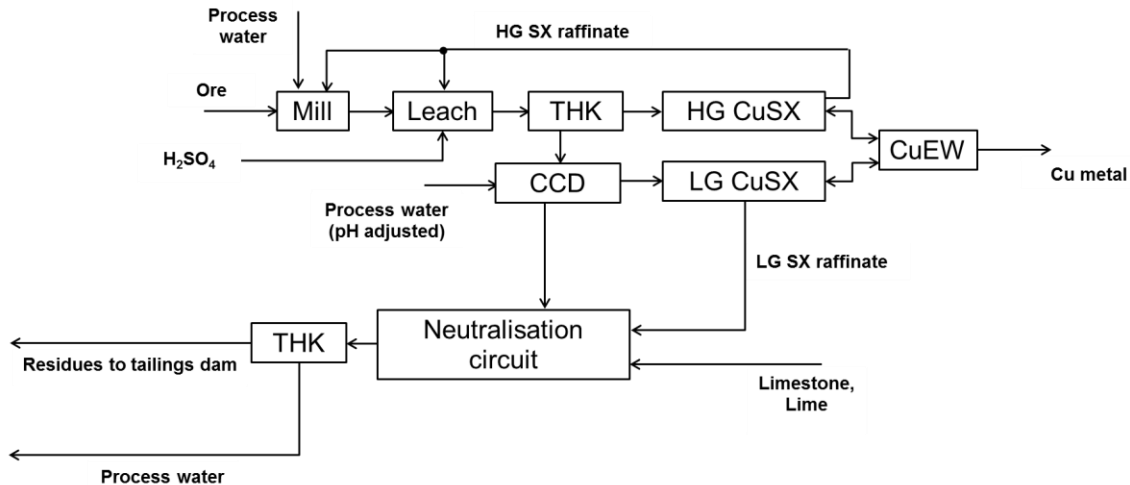


Figure 1. Base-case flowsheet with no Co recovery.

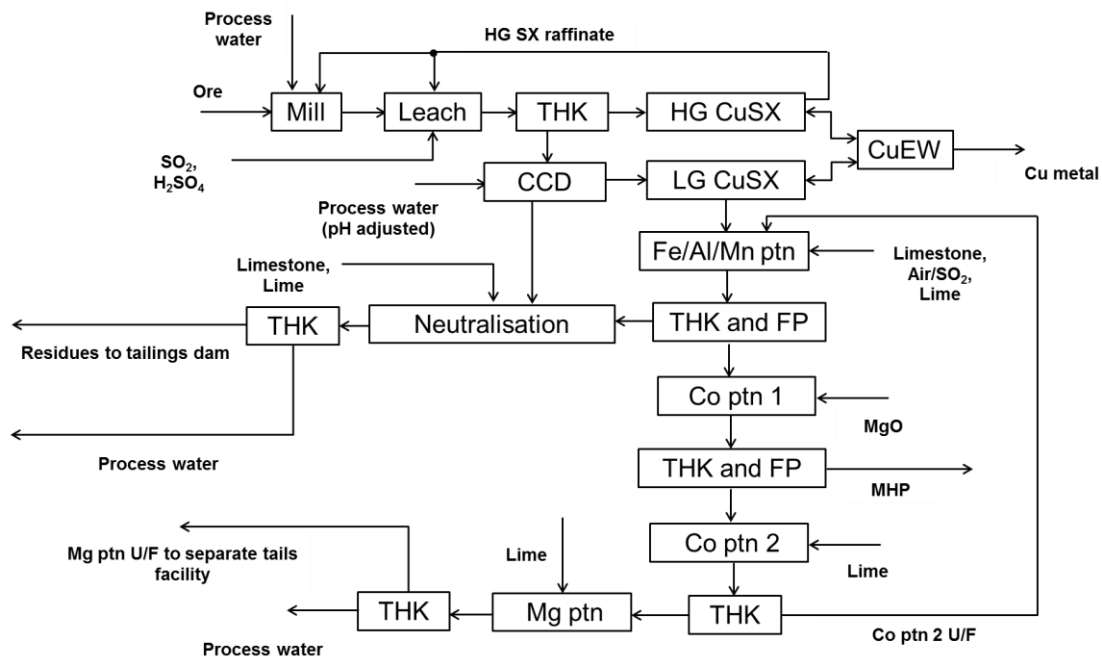


Figure 2. Typical MHP flowsheet for African Copperbelt ores.

Mass Balance Summary and Cost Estimation

High-level mass balances were conducted for a base-case Cu flowsheet (without Co recovery), high-purity MHP flowsheet and direct CoEW flowsheet using *SysCAD* software. Cu:Co grade ratios of 10:1 and 5:1 were evaluated for the three flowsheets at a constant Cu grade of 5.5% (w/w), at 1.09% Co and 0.55% Co respectively. The run-of-mine (ROM) throughput was 185 t/h, and the Cu and Co leach

efficiencies were kept constant at 90% and 88%, respectively. The direct CoEW flowsheet was simulated at 2 g/L delta Co and a 0.6% Co loss to the anode sludge was assumed across the EW cell. An assumed Co loss across Fe/Mn/Al precipitation, for both flowsheets, was 5%. In the base case flowsheet, the bleed stream from CuSX was neutralised and stored in a tailings facility, hence no Co product. This allows the cost of producing Cu to be separated from the additional cost of producing a Co by-product for both MHP and CoEW flowsheets. The mass balance for the upfront Leach-CuSX-EW circuit was fixed for both flowsheets. A plant utilisation and availability of 89% per year was assumed for all mass balance calculations. The mass balance results are listed in Table II.

Figure 3. Direct CoEW flowsheet

Table II. Mass balance results for nominal MHP and direct CoEW flowsheets.

Parameter	Base case	MHP	CoEW	Base case	MHP	CoEW
	5:1 Cu:Co ratio			10:1 Cu:Co ratio		
Co recovery (%)	0	81	80	0	81	77
Co loss - leach tails (%)	100	12	12	100	12	12
Co loss - Fe/Mn residue (%)	0	4.6	5.6	0	4.4	7.2
Co loss - Fe/Mn (entrained) (%)	0	0.4	0.7	0	0.4	1.0
Co loss - CCD (entrained) (%)	0	0.7	1.1	0	0.7	1.5
Co loss - anode sludge (%)	-	-	0.9	-	-	1.3
Co product (dry tons) (t/a)	0	17 330	6 807	0	9 500	3 281
Co product purity (%)	0	40	97	0	37	94

The values used to calculate the price of MHP and Co metal are shown in Table III, and the operating cost estimations are given in Table IV. Reagent costs used were for delivery on site in the DRC. The transport costs for MHP and Co cathode are inclusive of material handling costs.

Table III. Revenue estimations.

Product	Nominal price (US\$/t)
MHP price (69 % of LME Co price)	20 010
Cobalt metal price (73% of LME Co price)	21 170
LME Cobalt metal price	29 000

Table IV. Major reagents and cobalt transport costs and Co revenue estimations.

US\$ million pa	Base case	MHP	CoEW	Base case	MHP	CoEW
	5:1 Cu:Co ratio			10:1 Cu:Co ratio		
Cost component						
Cobalt product transport	0	11	4	0	6	2
MgO for Co ppt	0	11	-	0	7	-
Power for Co EW	-	-	4	-	-	2
Fresh acid	23	23	21	21	21	20
Total limestone	9	21	23	9	22	23
SO ₂	0	9	9	0	9	9
Total lime	21	14	7	19	11	6
Total	53	89	68	49	77	62
Revenue component						
Co Revenue	0	139	140	0	70	65

The major cost savings for direct CoEW are lower Co product transport costs and elimination of MgO, which consequently decreased the lime consumption. The elimination of MgO from the Co circuit will have an added benefit of reducing the environmental footprint because of the elimination of Mg(OH)₂ residues from Mg precipitation. The carbon footprint of the Co process will also be reduced due to the fact that the MgO is usually imported from USA or Australia.

The largest reagent costs for MHP and direct CoEW flowsheets were acid and limestone. Based on the nominal flowsheet conditions, the cost of producing Cu metal only was estimated at US\$ 53 million and US\$ 49 million for the 5:1 and 10:1 Cu:Co ore ratio respectively. The total cost of producing Co metal by direct CoEW could potentially decrease by 24% (5:1 ore ratio) and 19% (10:1 ore ratio), when compared with the cost of producing MHP. The Co revenue for the MHP and Co metal was similar at the 5:1 ore ratio, and the Co revenue for the MHP was ~7% higher than for Co metal at the 10:1 ore ratio, due to the lower Co recoveries in the CoEW flowsheet. The diminished impact of Co metal revenue could also be due to the conservative Co metal price. These results suggest that OPEX savings would be the main driver for increased profitability of the Co circuit and not the Co revenue.

Based on these positive preliminary cost estimates, an OoM desktop study was conducted to determine the CAPEX required for the direct CoEW flowsheet and to determine more accurate OPEX estimates. The flowsheets were evaluated at the two Cu:Co ratios to evaluate the effect of Co grade on the outcome of the economic evaluation. Two different sources of power supply, hence power costs, were evaluated, namely; power supply from the DRC power grid (SNEL-state power) and the worst-case scenario where the entire power requirement of the MHP and CoEW flowsheets is supplied using diesel generators. The CoEW test work results and the mass balances conducted provided the inputs that were used in the simulations for the techno-financial evaluation study.

TECHNO-FINANCIAL EVALUATION METHODOLOGY

Monte Carlo Simulations

Process Design Criteria (PDC) were generated for the Co purification/production circuit using in-house processing experience from previous base-metal projects. A stochastic approach was followed using Monte Carlo simulations. Different permutations of the mass balance were developed to provide a range of values for reagent consumption rates and revenue losses, across which probability distributions could be applied for use in Monte Carlo simulations. The permutations were generated by simulating maximum, nominal and minimal values of three main variables; which were: filter press wash efficiency, precipitation/co-precipitation extents and reagent utilisation extents. Utilizing these probability distributions in the differential discounted cash flow (DCF) model allowed the following to be determined:

- whether direct CoEW offered significant higher value over the MHP flowsheet when compared to the base case (no Co product);
- identifying key model drivers;
- quantifying uncertainty.

As illustrated in Figures 2 and 3, the front-end circuit was considered common to both flowsheets and was thus not included in the capital expenditure analyses. The front-end circuit includes: milling, leach, counter-current decantation, tails neutralisation, HG/LG solvent extraction, and Fe/Al/Mn precipitation. The front-end circuit was, however, included when calculating the OPEX for the three flowsheets, as the direct CoEW flowsheet involves recycling a portion of the electrowinning spent electrolyte to the leach circuit to increase Co tenor to CoEW and reduce the leach acid requirement.

The techno-financial evaluation was done on a “bare-bones” basis, in real terms and does not consider the effects of taxes, interest, financing models or any escalation; a 10% discount rate was used. Note that the costs shown are not to be regarded as definitive, but rather differential costs.

CAPEX Comparison Basis

An extensive spreadsheet-based analysis model was developed for this evaluation. The direct CoEW process input used for the calculations was a current efficiency of 35% at 150 A/m². All equipment was of standard supply. The main CAPEX considerations include:

- Differences in major mechanical equipment;
- A typical design criteria for each flowsheet in support of mass balancing and equipment sizing;
- Mechanical equipment costs determined from recently executed studies as well as DRA’s internal database;
- Internal DRA factors applied for civils, structural (supply and erection), platework (supply and erection), mechanical erection, piping (supply and installation), electrical, control and instrumentation (supply and installation), transport, project services, and Preliminary and General costs (P&Gs).

OPEX Comparison Basis

Operating cost estimates were based on the outcomes of the preliminary mass balances conducted using *SysCAD* and the PDC generated. Triangular distributions were applied to account for uncertainty associated with the mass balance results. Reagent costs from DRA’s database were used to calculate the OPEX. The major OPEX considerations included:

- Reagent costs estimated from DRA’s recently updated (2013) reagent supply database;
- Reagent consumption rates, determined from high-level mass balances, and include: sulphuric acid for leach; lime, limestone and MgO for pH control and to effect precipitation within the

relevant unit operations; SO₂, in conjunction with air, for the oxidation of Fe and Mn in the Fe/ Al/ Mn precipitation step;

- Power, labour and operating maintenance calculated did not have a significant effect on the differential OPEX. It was also found that the power required for CoEW was offset by the power required for the MHP drying plant.

TECHNO-FINANCIAL EVALUATION RESULTS

CAPEX Comparison Basis

The results from the CAPEX calculations are shown in

Table V. The CAPEX required for MHP recovery was US\$ 34 million and US\$ 57 million for the 5:1 Cu:Co ratio for 100 % grid- and 100% generator-supplied power, respectively, when compared with the base case. In comparison, the CAPEX required for CoEW flowsheet was US\$ 70 million and US\$ 99 million for the 5:1 Cu:Co ratio for 100 % grid- and generator-supplied power, respectively, when compared with the base case. The increased CAPEX is mainly due to the large cell-house size resulting from the low current efficiency.

Similarly, the CAPEX required for MHP recovery was US\$ 30 million and US\$ 45 million for the 10:1 Cu:Co ratio for 100 % grid- and generator-supplied power, respectively, when compared with the base case. In comparison, the CAPEX required for CoEW flowsheet was US\$ 44 million and US\$ 61 million for the 10:1 Cu:Co ratio for 100 % grid- and generator-supplied power, respectively, when compared with the base case.

Table V. CAPEX results.

Area	Base case	MHP Circuit	CoEW Circuit
Co #1 precipitation	N/A	Yes	N/A
Co #2 precipitation	N/A	Yes	N/A
Mg precipitation	N/A	Yes	N/A
Direct CoEW	N/A	N/A	Yes
Spent electrolyte precipitation	N/A	N/A	Yes
5:1 Cu:Co Ratio CAPEX estimate			
100 % grid power (US\$)	0	33 816 746	69 735 169
100 % generator power (US\$)	0	56 837 992	98 713 926
10:1 Cu:Co Ratio CAPEX estimate			
100 % grid power (US\$)	0	29 764 242	44 021 175
100 % generator power (US\$)	0	45 254 341	60 810 882

Net Present Value (NPV) Analysis

NPV Results for Grid Power (SNEL)

The differential discounted cash-flow model outputs from the Monte Carlo simulation for the 5:1 and 10:1 Cu:Co ore ratios for the MHP and CoEW flowsheets using 100% grid power are shown in Figure 4 and Figure 5. These indicate the differential NPV for the MHP versus the base case relative to the differential NPV for the direct CoEW versus the base case. The graphs represent the statistical probability of achieving a positive or negative differential NPV based on the assigned probability distributions, with the expected values indicated by the central tendency of the distribution, while the standard deviation reflects the variability or uncertainty due to estimates being used.

The results for the 5:1 ore ratio show that, within a 90% confidence range, the direct CoEW flowsheet can potentially achieve an expected differential NPV of between US\$ 67 million and US\$ 144 million,

with a mean value of US\$ 105 million in comparison with the MHP flowsheet. This potential increase can be attributed to the OPEX savings because the Co revenue for the two flowsheets was similar. As expected, the NPV values for the 10:1 ore ratio were lower due the lower Co recoveries observed for the CoEW flowsheet. The direct CoEW flowsheet can achieve a differential NPV of between US\$ 41 million and US\$ 94 million, with a mean value of US\$ 68 million, in comparison with the MHP flowsheet. The OPEX savings for the CoEW flowsheet were high enough to achieve a potential increase in NPV of US\$ 68 million, although the Co metal revenue was less than the MHP revenue.

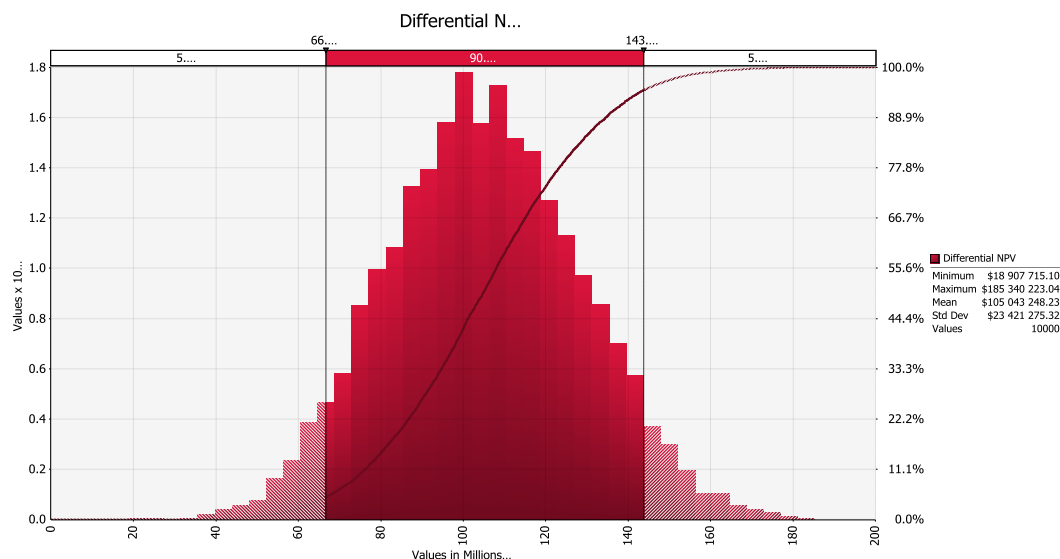


Figure 4. Differential NPV for CoEW flowsheet versus MHP flowsheet at 5:1 ore ratio (grid power).

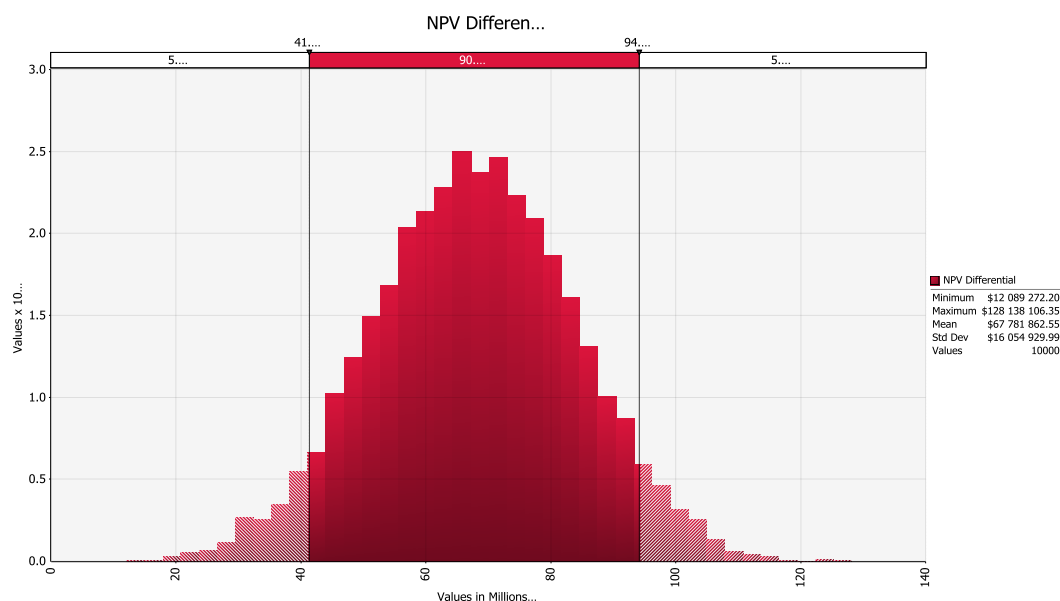


Figure 5. Differential NPV for CoEW flowsheet versus MHP flowsheet at 10:1 ore ratio (grid power).

NPV Results for Generator Power

The differential discounted cash flow model outputs from the Monte Carlo simulation for the two ore ratios for the MHP and CoEW flowsheets, using 100% generator power are shown in Figure 46 and 7. The results for the 5:1 ore ratio (Figure 6) show that, within a 90% confidence range, the direct CoEW flowsheet can potentially achieve an expected differential NPV of between US\$ 36 million and

US\$ 113 million, with a mean value of US\$ 74 million in comparison with the MHP flowsheet. The NPV values for the 10:1 ore ratio (Figure 7) show that the direct CoEW flowsheet can achieve a higher expected differential NPV of between US\$ 35 million and US\$ 87 million, with a mean value of US\$ 61 million, in comparison with the MHP flowsheet.



Figure 6. Differential NPV for CoEW flowsheet versus MHP flowsheet at 5:1 ore ratio (generator power).

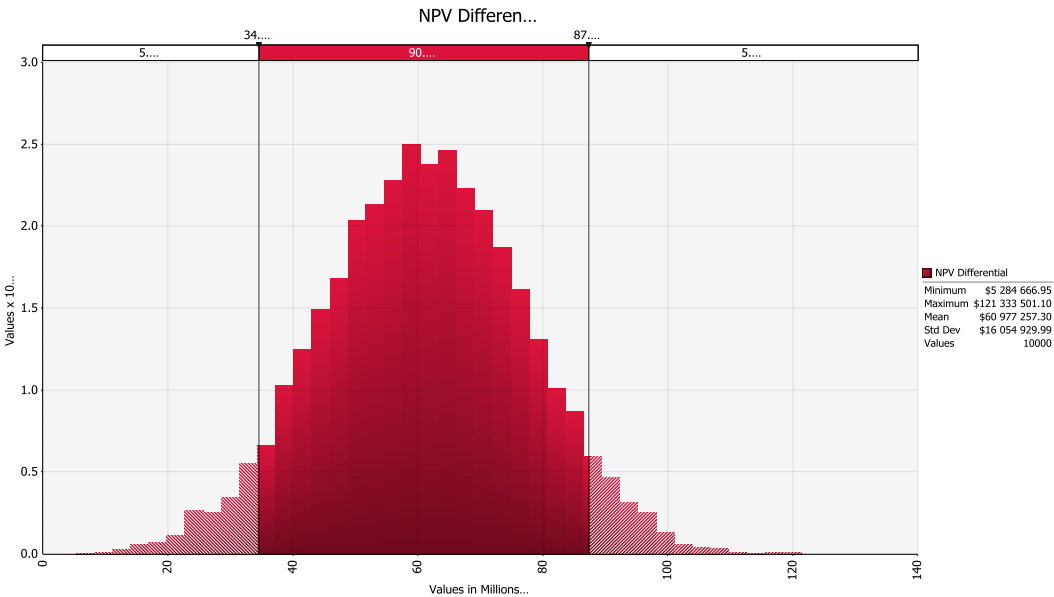


Figure 7. Differential NPV for CoEW flowsheet versus MHP flowsheet at 10:1 ore ratio (self-generated power).

Sensitivities and Value Drivers

The sensitivity of the calculated NPV for the MHP and CoEW flowsheets with respect to the various inputs for the 5:1 and 10:1 were similar; however, the 10:1 ratio, which represents the worst-case scenario for the CoEW flowsheet is discussed. The results for grid and generator power supply are illustrated using the tornado graphs in Figure 8 and 9Error! Reference source not found.. The graphs depict single-variable sensitivity analyses, which enable determination of the inputs that have the greatest effect on the NPV of the model. It can be seen that, both MHP and direct CoEW are better financial propositions relative to the base-case flowsheet because in no instance does the differential

comparison, when considering a single variable only, favour the latter. The Co recovery was the single variable that had the most significant effect on the NPV for both power-supply source scenarios, but the Co recovery did not change the decision, merely the value of the benefit. Furthermore, the tornado graph illustrates that the primary focus for techno-financial evaluation refinement should be placed on the CoEW flowsheet optimisation to minimise Co losses in the Co circuit to minimise uncertainties.

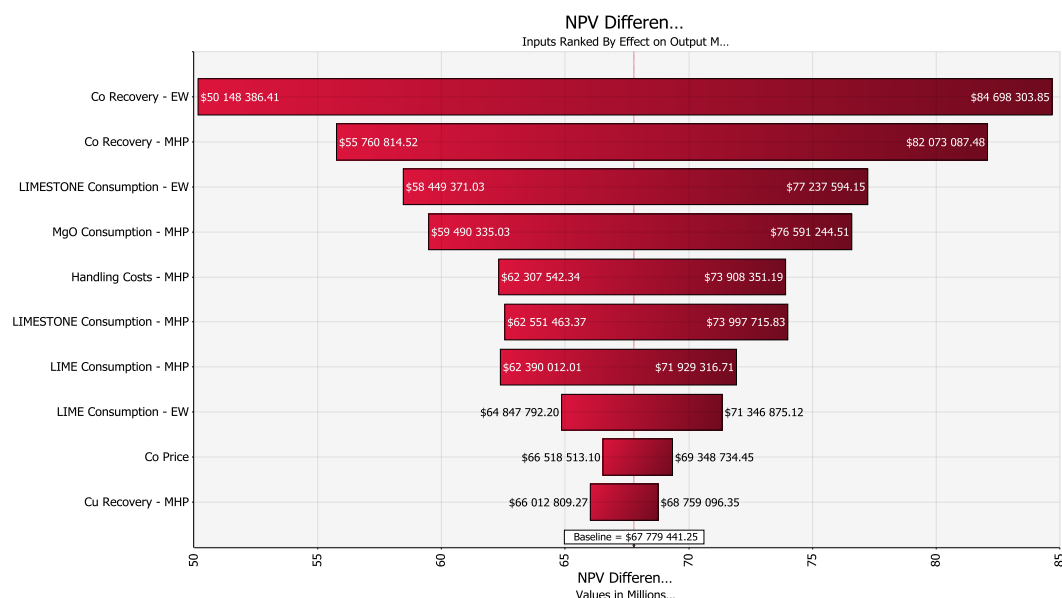


Figure 8. Most influential variables affecting the differential NPV for grid power (SNEL) (10:1 ore ratio).

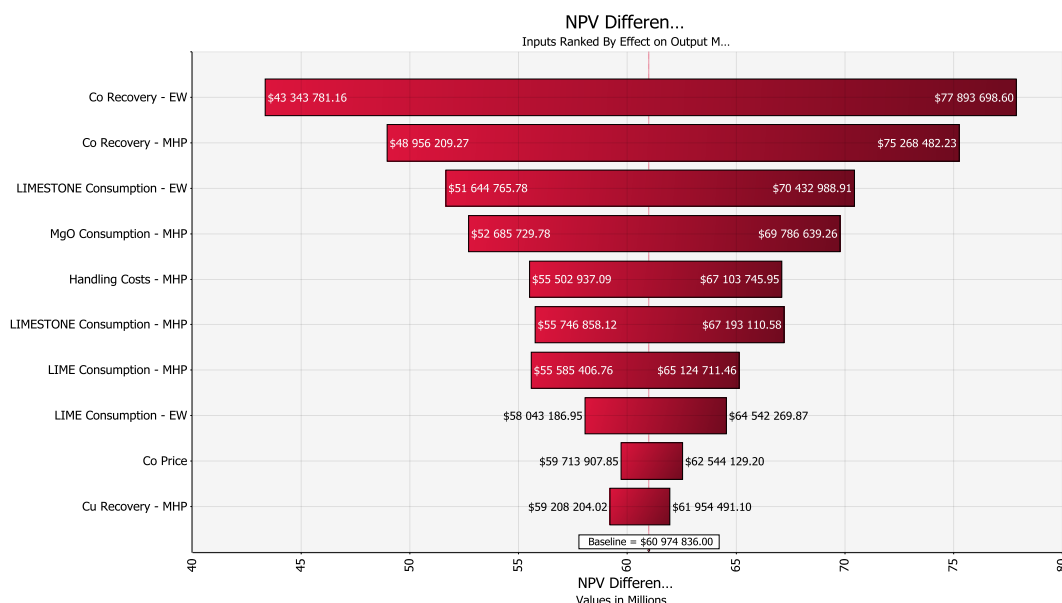


Figure 9. Most influential variables affecting the differential NPV for self-generated power (10:1 ore ratio).

CONCLUSIONS

Direct CoEW was developed to produce unrefined cobalt metal as an alternative to a MHP intermediate product, with the aim of improving profitability of the African Copperbelt Cu-Co process flowsheet. The direct CoEW process was proven to be feasible through laboratory and pilot-plant test work. Mass balance and preliminary cost estimates results showed that the main economic

driver for the CoEW flowsheet would be the operating cost savings resulting from the elimination of MgO, and consequently lower lime addition. The Co product transport costs for Co metal would also be lower when compared with MHP. In addition to the potential economic benefit, MgO elimination has the added advantage of reducing the environmental and carbon footprint of the Co process.

The difference in CAPEX when using generator versus grid power supply for CoEW and MHP flowsheets was similar: US\$ 23 million at 5:1 ore ratio and US\$ 15 million at 10:1 ore ratio for the MHP flowsheet, and US\$ 29 million at 5:1 ore ratio and US\$ 17 million at 10:1 ore ratio for the CoEW flowsheet. The NPV results showed that the direct CoEW flowsheet can potentially be more profitable than the MHP flowsheet, due to the lower OPEX for producing Co metal compared with MHP. The mean NPV for CoEW flowsheet when compared with the MHP flowsheet for the worst-case evaluated, i.e. 10:1 ore ratio and generator power supply, was US\$ 61 million; and it was US\$ 105 million for the best case evaluated, i.e. 5:1 ore ratio and grid power supply. The NPV was most sensitive to the Co recovery.

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