Supplementary material for Paricheh and Osanloo, "Concurrent open-pit mine production and in-pit crushing-conveying system planning", *Engineering Optimization*, 2019.

1 Parameters preparation

1.1 Haulage costs

The term haulage cost of ore blocks can be divided into two separate parts. The first part includes the trucking cost from the block to the primary crusher and the second part is the conveying cost of the block from the primary crusher to the secondary crusher or processing plant. For waste materials, the haulage cost just includes the trucking cost. It is worth noting that, in this research, the conveying cost from the primary crusher to the secondary crusher is considered a part of mining cost not processing cost. Equation SM.1 shows how one can calculate the haulage cost (HC_{bj}) to any destination.

$$\mathrm{HC_{bj}} = \mathrm{THC_{bj}} + \mathrm{CHC_{j}} \qquad \text{(SM.1)}$$

Where THC_{bj} is the trucking cost of material (\$/tonne) from block b to destination j and CHC_j is the conveying cost (\$/tonne) from destination j to the secondary crusher. For waste blocks, the term CHC is equal to zero. The truck operating cost can be calculated by using Equation SM.2.

$$THC_{bj} = \frac{TCT_{bj} \times THOC}{60 \times TC \times J_e \times F_s \times F_f} \qquad \text{(SM.2)}$$

Where TCT_{bj} is the truck cycle time in minute from block b to destination j, THOC is the truck operating cost (\$/hour), TC is the truck capacity in tonne, J_e is the job efficiency, F_s is swell factor of materials and F_f is fill factor of the trucks. The truck cycle time is a function of haulage distance, truck speed, maneuvering, loading and dumping times. The truck haulage distance from any point in the pit to any destination in or out of the pit also consists of three parts. The first and the last parts are usually horizontal distances in or out of the pit (Equation SM.3). The second part is usually haulage distances on the in-pit ramping systems (Equation SM.4).

$$HD_{bj} = \sqrt{(X_b - X_j)^2 + (Y_b - Y_j)^2} \qquad \text{(SM.3)}$$

$$RD_{bj} = \frac{|Z_b - Z_j|}{sin\,\alpha} \qquad \text{(SM.4)}$$

Where HD_{bj} is the horizontal truck haulage distance between block b and destination j, X_b is the x-coordinate of block b and X_j is the x-coordinate of destination j, Y_b is the y-coordinate of block b and Y_j is the y-coordinate of destination j, RD_{bj} is the truck haulage distance on the ramping system from block b located on level Z_b to destination j located on level Z_j, α is the gradient of the ramping system. Remember that these distances are estimated distances and the exact distances are not known until the ramping system is located. Loaded trucks carry the materials uphill and empty trucks move downhill if the destination is at an upper level compared to a given block. Inversely, loaded trucks will handle the materials downhill and empty trucks move uphill if the destination is at a lower level than a given block. With that, Equations SM.5-SM.6 are also used for estimating the truck cycle times in the two mentioned situations, respectively.

$$TCT_{bj} = \frac{60}{1000}\left(\frac{RD_{bj}}{USL} + \frac{RD_{bj}}{DSE} + \frac{HD_{bj}}{SSL} + \frac{HD_{bj}}{SSE}\right) + MA + LO + DU \qquad \text{(SM.5)}$$

$$TCT_{bj} = \frac{60}{1000}\left(\frac{RD_{bj}}{DSL} + \frac{RD_{bj}}{USE} + \frac{HD_{bj}}{SSL} + \frac{HD_{bj}}{SSE}\right) + MA + LO + DU \qquad \text{(SM.6)}$$

Where USL and USE are the truck speeds (km/h) in uphill when the truck is loaded and empty, respectively. Similarly, DSE and DSL are the truck speeds (km/h) in downhill when the truck is empty and loaded, respectively. SSE and SSL are the speeds of empty and loaded trucks (km/h) on a flat surface, MA is considered as total maneuvering time in both loading and dumping sites, LO is the loading time and DU is considered as the dumping time. Note that depending on the crusher height, trucks must usually carry the materials to one or two level/bench above the in-pit crusher site to dump the materials onto the apron feeder.

Regarding the conveyor part, an IPCC system has three conveyor lines (Figure 1). The first one in the pit and the last one on the ground usually carry the materials on a flat surface (continues horizontal arrows in Figure 1). The second line called trunkline conveyor does the major part of the material handling process since it takes the materials out from a lower level in the pit (dashed arrow in Figure 1). Both capital and operating cost of these three lines are to be estimated properly. The trunkline can exit from the pit through using high angle conveyors, dedicated ramp slots, existing truck ramping systems or tunnels. Therefore, the best method of exiting the trunkline from the pit must be selected first. In this study, it is supposed that a high angle conveyor is the best option for exiting the trunkline from the pit. In order to analysis the cost of different conveyor lines, a theoretical foundation have been developed by the authors which is not within the scope of this paper and its results will be disseminated in another publication (Paricheh and Osanloo 2018). In this study, this theoretical foundation is used to estimate both capital and operating costs of conveyor lines.

1.2 Dynamic block economic value

Among the parameters described in the paper, the parameter BEV is the most important one since it controls the yearly incomes. Regardless of the time value of money, the exact block values are not known until the final destinations of the blocks are known. To cope with this, in this study, the BEV was calculated based on the block's destination. The general form of the dynamic BEV calculation can be expressed by Equation SM.7.

$$BEV_{bj} = \begin{cases} T_b\left\{\left[10 g_b y(p - sc) - pc\right] - rc - HC_{bj}\right\} & if \quad j > 1 \\ \quad or & \\ -T_b(rc + HC_{bj}) & if \quad j = 1 \end{cases} \qquad \text{(SM.7)}$$

Actually, in this study, discriminating the ore and waste materials is done during the optimization process. The BEV and also the minimum grade of the yearly extracted material will be changed since the haulage costs and the destinations are changed.

1.3 Truck book value

In this study, double declining deprecation balance method was used in order to calculate the amount of truck's yearly depreciation. The double declining balance method is a type of declining balance method with a double depreciation rate. Actually, it uses a depreciation rate that is twice the straight-line method rate. Suppose the useful life of trucks is denoted by UL. So, the depreciation rate would be 2/UL. Note that the depreciation values are used for estimating the book (or salvage) value of trucks used, rather than for tax-offset purposes. The book values of an asset in year t can be calculated by subtracting the summed values of the depreciation until year t from its initial value. Equation SM.8 wholly represents the yearly truck book values. In this case, since there is no preexisting equipment in the fleet and also trucks are not held idle, the book value is a function of truck age.

$$BV_t^l = D_t \times PC \times (1 - 2 / UL)^l \qquad \text{(SM.8)}$$

1.4 Valuable operating hours of trucks by age bin

Like other pieces of equipment, once a truck is purchased and used, it begins to wear out and suffers mechanical problems eventually. As trucks get older or move to the higher age bins, the Valuable Operating Hours (VOH) of trucks are gradually decreased. The VOH is a time usage metric which considers that portion of available time the equipment can operate effectively. Indeed, it can be calculated by subtraction of non-scheduled times, operating standbys, operating delays, performance losses and quality losses from the annual available operating hours (Dzakpata *et al*. 2016). Totally, decreasing the VOH can be interpreted as increasing repair, and operating costs. Therefore, there is a decision which must be taken regarding determining when it is no longer economically feasible to repair a broken truck. In this study, this maximum useful life of trucks is assumed as 10 years. In other words, the trucks work no longer than 10 years. Figure SM.1 shows how the VOHs for trucks decrease by age bins. Discretization of total VOHs into stepwise functions have also been done previously by Burt *et al*. (2016), Burt and Caccetta (2014) and Topal and Ramazan (2010). Similarly, if the VOH is not the case, the hourly operating cost can be discretized by age brackets.

Figure SM.1. Valuable operating hours of trucks by truck age

In the current study, the sizes of age bins are defined as a year. If a truck in age bin l works during the year t, it would jump into age bin l+1 in the next year t+1. It is assumed that the VOHs are given as those presented in Table SM.1.

Table SM.1. Proposed VOHs of trucks by age bin

Age bin (year)	[0-1)	[1-2)	[2-3)	[3-4)	[4-5)	[5-6)	[6-7)	[7-8)	[8-9)	[9-10)	[10-11)
VOH (hour)	4000	4000	4000	4000	4000	3000	3000	2000	2000	1000	1000

The whole fleet of haulage has also a specific VOH. It is worth noting that the value of parameter U (i.e., Yearly crusher/conveyor throughput) can be calculated by multiplying the value of annual effective operating hours of the whole system (TS or IPCC) by the hourly crusher throughput (tonne/hour). The VOHs related to both T&S and IPCC systems have been calculated in details by Dzakpata *et al*. (2016) as 4000 and 3500 hours per year, respectively.

2 Ultimate pit limit determination

The UPL defines the economically extractable parts of the ground (i.e., mineral reserves) and it can be calculated using Equations SM.9-SM.13. Any part out of the UPL will not yield any profit. Equation SM.9 is the objective function that maximizes the revenue. Equations SM.10 and SM.11 are the constraints of the model. Indeed, Equation SM.10 defines the slope requirements and the last one (Equation SM.11) sets the binary condition for the variables. If a block is located inside the pit, the variable u_b takes number 1 and 0 otherwise.

$$\max \sum_{b} BEV_b \, u_b \qquad \text{(SM.9)}$$

$$u_b \le u_{b'} \quad \forall b \in B; b' \in \Gamma_b \qquad \text{(SM.10)}$$

$$u_b \in \{0,1\} \qquad \text{(SM.11)}$$

There is a difference between BEV_b and BEV_{bj} described in Equation SM.7. The latter is defined based on different block destinations and the former is based on a predefined destination of the block using the general concept of break-even cut of grade (Equations SM.12-SM.13). The parameters *mc* is the predefined average mining cost of a block.

$$BEV_b = \begin{cases} T_b \{[10 g_b y(p - sc) - pc] - mc\} & \text{if} \quad g_b \ge g_{breakeven} \\ -T_b mc & \text{otherwise} \end{cases} \qquad \text{(SM.12)}$$

$$g_{breakeven} = \frac{pc + mc}{y(p - sc)} \qquad \text{(SM.13)}$$

3 Two-dimensional hypothetical examples

Two hypothetical 2D examples of a copper deposit were built for evaluating the performance of the proposed MILP model (Figures SM.2 and SM.3). In the first example, the ore body has an outcrop and continued from the surface into the deep, while in the second example; the ore body has been covered by a vast amount of waste or overburden. The main reason for building such

2D models is that the MILP model is computationally intractable in real large scale open pits. Each sub-problem described above is individually NP-hard. Therefore, solving a real case requires efficient solution techniques. This paper is just going to show how the proposed model can adequately overcome an important and unanswered problem in open pit mine planning. A small 2D example helps us obtain the optimum solutions in a reasonable time scale and also see the different aspect of the model clearly. In addition, the 2D example shows the changes in the extraction sequences of the blocks, pit deepening rates and mining directions in a more sensible way. As well, it can be used as a useful tool for building efficient solution techniques. First of all, the UPLs associated with both examples were determined by using a simple integer programming model described in Equations SM.9-SM.13. The darker blocks in Figures SM.2 and SM.3 represent the UPLs for these cases.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04	0.01	0.45	0.33	0.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.04	0.67	0.91	0.34	0.4	0
0	0	0	0	0	0	0	0	0	0	0	0	0.23	1.5	0.23	1	0.5	0.6	0	0
0	0	0	0	0	0	0	0	0	0	1.11	1	0.09	1	0.35	1.5	0.21	0	0	0
0	0	0	0	0	0	0	0	0	0.89	1.19	0.47	1.2	0.23	0.71	1	0	0	0	0
0	0	0	0	0	0	0	1.41	0.99	1.30	0.83	0.09	0.32	0.39	0.92	0	0	0	0	0
0	0	0	0	0	0	0.41	0.32	0.46	0.99	0.88	1.49	0.42	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0.34	1.3	0.7	0.84	0.53	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0.9	1.2	0.78	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Figure SM.2. Example 1 (numbers are copper grades in percent), lighter dark blocks are representing the ore-body, the white blocks are waste rock surrounding the ore-body, the darker blocks are also showing the pit boundaries

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.02	0.76	1.29	0.44	0.70	0.34	0.00	1.11	1	0.09	1	1	1.5	1	0	0	0
0	0	0	0	0.21	0.19	0.81	1.35	0.45	0.89	1.19	0.47	1.5	1	1.5	1.5	0	0	0	0
0	0	0	0	0	0.46	1.38	1.41	0.99	1.30	0.83	0.09	1	1	1.5	0	0	0	0	0
0	0	0	0	0	0	0.41	0.32	0.46	0.99	0.88	1.49	0.42	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0.34	1.3	0.7	0.84	0.53	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0.9	1.2	0.78	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Figure SM.3. Example 2 (numbers are copper grades in percent), lighter dark blocks are representing the ore-body, the white blocks are waste rock surrounding the ore-body, the darker blocks are also showing the pit boundaries

4 Technical and economic data

Table SM.2 shows the technical and economic data used in the optimization process. These data are those used in the MILP models directly or indirectly. Actually, the indirect usage of the data means that they are used for calculating the parameters based on what explained in Sections 1 and 2 of this supplemental material and those explained in Paricheh and Osanloo 2018.

Table SM.2. The proposed technical and economic data

Parameter type	No	Parameter		Value	Unit
Technical	1	Rock density		2.5	t/m^3
	2	Ramp slope angle		10	%
	3	Block dimension		100×100×100	m×m×m
	4	Distance from the pit exit point to the ex-pit primary crusher		2	Km
	5	Distance from the pit exit point to the waste dump		2	Km
	6	Conveyor length from the primary ex-pit crusher to the secondary crusher		1	Km
	7	Truck capacity		100	Tonne
	8	Recovery		80	%
	9	Mine capacity		15-18	Million tonne/year
	10	Mill capacity		8-10	Million tonne/year
		Crusher/Conveyor capacity		4000	Tonne/hour
	11	Head grade		0.4-1	% cu
	12	Truck cycle time components	Loading+queue	5	Minute
			Dumping	1	Minute
			Maneuvering	3	Minute
	13	Truck speed	Uphill	20	Km/h
			Downhill	30	Km/h
			Surface	25	Km/h
	14	Job efficiency		80	%
	15	Swell factor of material		80	%
	16	Bucket Fill factor of truck		80	%
	17	Annual Effective operating hour of T&S system		4000	Hour/year
	18	Annual Effective operating hour of IPCC system		3500	Hour/year
Economic	19	Commodity price		4	$/kg
	20	Processing cost		7	$/tonne
	21	Refining and selling cost		0.7	$/kg
	22	Average mining cost (including haulage cost)		1.5	$/tonne
	23	Removal cost (mining cost excluding the haulage cost)		0.7	$/tonne
	24	Discount rate		10	%
	25	Purchasing cost of truck		1.5	$ million
	26	Truck operating cost		150	$/hour
	27	Purchasing cost of crusher	Ex-pit crusher	7	$ million
			In-pit crusher	7	$ million
	28	Crusher relocation cost		2	$ million
	29	Percentage of purchasing cost as installation cost of equipment		3	%
	30	Electricity price		0.06	$/Kwh
	31	Labor cost		250	$/shift
	32	Percentage of purchasing cost as repair and maintenance cost		2	%

5 Results associated with the second example

In this section, for the second example, similar results as those provided for the first example in the main text are provided. The results can be interpreted similarly.

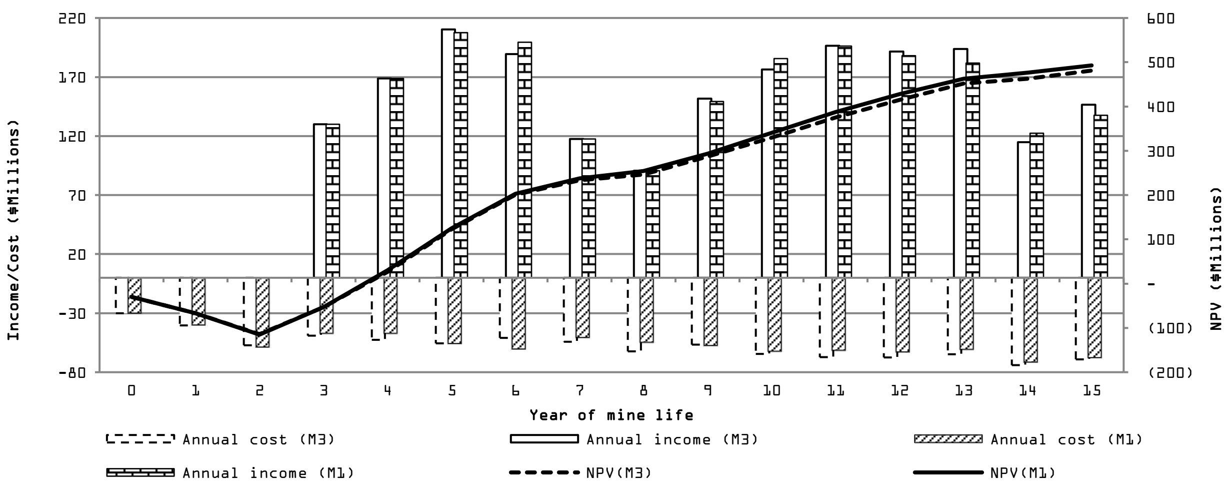
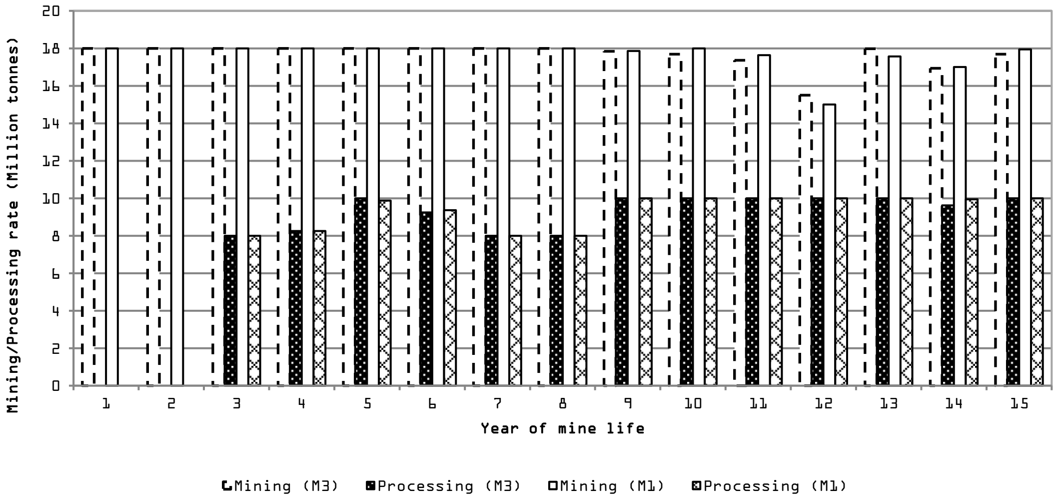


Figure SM.4. Comparison of annual incomes/costs and cumulative NPVs for scenarios M1 and M3 (Example 2)



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- Figure SM.5. Comparison of annual mining and processing rates for scenarios M1 and M3 (Example 2)

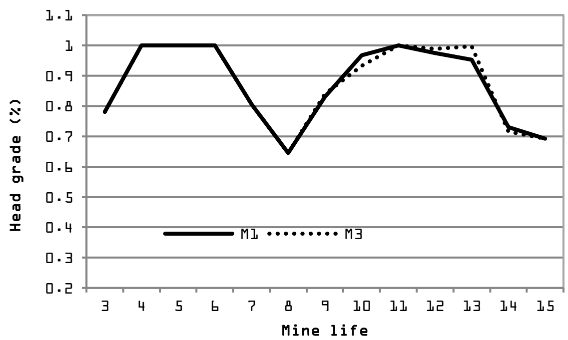


Figure SM.6. Comparison of annual head grades for scenarios M1 and M3 (Example 2)

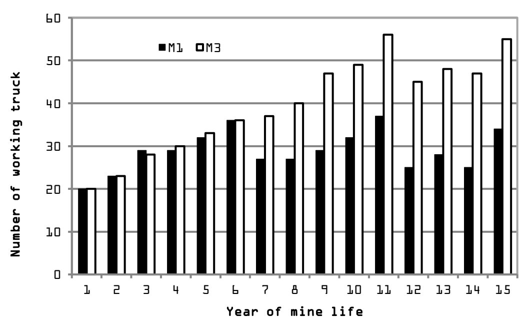
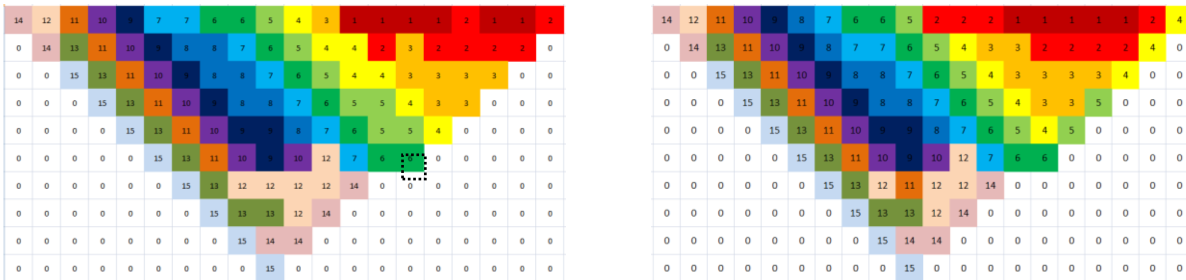


Figure SM.7. Comparison of working trucks during the mine life for scenarios M1 and M3 (Example 2)



a) b)

Figure SM.8. Comparison of extraction sequences for the second example (numbers indicate the years of extraction), a) M1, b) M3

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