Production Scheduling of Open Pit Metal Mine with Ecological Cost

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Abstract: The ecological costs related to the various optimized production schemes were calculated based on the designed ultimate pit. Moreover, the influence of the ecological costs on the selection of production schemes was discussed. In one designed pit, a series of geologically optimum pushbacks with sufficiently small increment were produced using the floating cone method founded on the principle of the highest metal content. Then all the pushbacks were reordered by the dynamic network diagram. The production scheme with the maximum NPV route was considered as the optimum one. The ecological impacts produced by mining were quantified and the ecological cost calculation models, which contain the direct eco-value loss, the indirect eco-value loss, the eco-restoration cost and the carbon emission cost were proposed. In one big open pit mine case, various production schemes were optimized and the one with maximum NPV was selected without taking into account the eco-costs. The scheme with the maximum comprehensive profit was obtained by calculating the eco-cost of each scheme. The results showed that the best scheme considered with the eco-cost was not the scheme with the maximum NPV. Therefore, the eco-cost presents the effect on the selection of the best production scheme.

Keywords: open pit mine, production scheme, optimization, ecological cost

1. Introduction

Optimizing production scheme is to determine the mining quantities of ore and rock, the pushing position of stope each year, and maximize the NPV of mine. In the theory, production scheming optimization has gone through trial and error (Pana and Carlson 1966), linear programming method (Johnson 1968), mixed integer programming (Gershon 1983), integer mapping (Kim and Cai 1990), dynamic programming et al (Gu et al 2014). In recent years, the study on production scheduling optimization has been focused on two aspects. On the one hand, the study is to solve the investment risk caused by the uncertainties of economic and geological environment (Ramazan and Dimitrakopoulos 2013, Marcotte and Caron 2010, Lamghari and Dimitrakopoulos 2012, Godoy and Dimitrakopoulos 2004, Benndorf and Shishvan 2014). On the other hand, the emphasis of the study was on reducing the problems for the optimization algorithm, to make it more efficient and practical (Cullenbine et al 2011, Shishvan and Sattarvand 2015, Askari-Nasab et al 2011, Nasab et al 2010). However, different production schemes cause different damage of mine land and pollutant emission, thus triggering environment problem. With the improvement of people's consciousness of environment protection, the environmental issue of mining has been attracting more and more attention.

Based on the theory of ecological footprint, Xu et al (2014) built ecological footprint model and ecological cost model of mine, and employed an iterative algorithm to optimize ultimate pit considering ecological cost, by which

maximum economic benefits and ecological benefits can be obtained. Badiozamani and Askari-Nasab (2014) optimized production scheme of open pit oil sand mine considering tailings pond reclamation. By studying the relation between mine transportation equipment performance and energy consumption, Peralta et al (2016) found that a reasonable maintenance schedule can improve the use of energy and reduce greenhouse gas emission by studying the relation between mine transportation equipment performance and energy consumption. Gholamnejad (2009) put ecological restoration cost into cutoff calculation and optimized the best cutoff via lane method. So far, researches on mine sustainable development are primarily still in qualitative analysis phase. The environment disruption, society issues and economic benefit caused by the mineral resources have not been quantified in the form of money.

In this article, ecological cost caused by mining activity is divided into direct eco-value loss, indirect eco-value, eco-restoration cost and carbon emission cost. Firstly, multi-production schemes are optimized via metal-miner software. Then ecological cost caused by different schemes is figured out. At last, influence of eco-costs on how to choose the production scheme is discussed.

2. The Model of Production Scheme Optimization

In a designed pit, if the excavation quantities are fixed in a given year, there are many sections which have the same excavation quantities and meet the requirement of working slope angle. The best choice of determining the optimum

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mining position in this year is to find out a section that contains the maximum metal content from all sections. The section is named geologically optimum working-slope pushback and showed by P . Cone elimination method is used to remove some blocks which meet the given increments (such as ΔP) and the average grade are minimum. Then, a series of nest pushbacks ($\{P^*\}_N$) which differ by ΔP are generated (Gu et al 2014).

After obtaining geologically optimum working-slope pushbacks ($\{P^*\}_N$), the production scheme optimization is to find out the optimum subsequence ($\{P^*\}_M$) from the $\{P^*\}_N$ (Gu et al 2011).

3. Ecological Cost Calculation

The environment problem caused by mining is transformed into the eco-cost which is considered in mine project evaluation and design optimization. It is the evaluation basis of achieving economy and ecology integral optimization. The eco-costs of resource exploitation contain four parts, direct eco-value loss, indirect eco-value loss, eco-restoration cost and the carbon emission cost.

3.1 Direct eco-value loss

Land acquisition cost is the fee of land usage right, which is needed to be paid for the landowners by the mine enterprise. It reflects the direct value loss of damaged land. So, Land acquisition price can show the direct eco-value loss. If mine requisitions land in phasing, the direct eco-value loss, $C_{Z,t}$, at time t is,

$$C_{Z,t} = A_{z,t} \cdot \frac{c_z(1+u)^t}{(1+d)^t} \quad (1)$$

where, $A_{z,t}$ is the area of land acquisition at time t , hm^2 ; c_z is the price of land acquisition at present, $\text{US}\$/\text{hm}^2$.

3.2 Eco-restoration cost

Eco-restoration cost is used to pay for recovering ecological function of damaged land by mining activity and conserving vegetation after reclamation project. The eco-restoration cost present worth, $C_{r,t}$, in $\text{US}\$$, at time t is,

$$C_{r,t} = A_{r,t} \cdot \frac{c_r(1+u)^t}{(1+d)^t} \quad (2)$$

where, $A_{r,t}$ is the area of restoration at time t , hm^2 ; c_r is the eco-restoration cost of forest, $\text{US}\$/\text{hm}^2$.

3.3 Indirect eco-value loss

Indirect eco-value loss is ecological service value loss of damaged land except direct eco-value. The land damaged by mining is primarily woodland. So, all damaged land can be equally regarded as the woodland. According to human understanding of forest ecological service function, the indirect eco-value is mainly reflected in the water conservation, wind prevention and sand stabilization, purifying environment, climate regulation, photosynthetic carbon fixation, releasing oxygen, soil conservation, nutrient cycling and maintaining bio-diversity et al.

(1) Purifying air value

Forest has the function of absorbing pollutant in the air and, such as CO_2 , SO_2 and NO_x , detaining dust and secreting bactericidin. The value of air purification, V_a , in $\text{US}\$/\text{a}/\text{hm}^2$, is calculated as:

$$V_a = q_f \lambda_c c_c + y_s c_s + y_n c_n + y_d c_d + y_g c_g \quad (3)$$

where, q_f is the net primary production (NPP) of woodland, $\text{t}/\text{hm}^2/\text{a}$; λ_c is the fixed parameter of CO_2 ; c_c is the treatment cost of CO_2 , $\text{US}\$/\text{t}$; y_s is the absorbing ability of SO_2 , $\text{t}/\text{hm}^2/\text{a}$; c_s is the treatment cost of SO_2 , $\text{US}\$/\text{t}$; y_n is the absorbing ability of NO_x , $\text{t}/\text{hm}^2/\text{a}$; c_n is the treatment cost of NO_x , $\text{US}\$/\text{t}$; y_g is the bactericidin secretory capacity of forest, $\text{t}/\text{hm}^2/\text{a}$; c_g is the price of bactericidin, $\text{US}\$/\text{t}$.

(2) Releasing oxygen value

Calculating oxygen releasing value of forest, V_o , in $\text{US}\$/\text{a}/\text{hm}^2$, is similar to carbon fixation value estimation:

$$V_o = q_f y_o c_o \quad (4)$$

where, y_o is the parameter of oxygen releasing; c_o is the production cost, $\text{US}\$/\text{t}$.

(3) Conserving water value

The water conservation value of woodland, V_h , in $\text{US}\$/\text{a}/\text{hm}^2$, is calculated as:

$$V_h = 10jkr_h c_h \quad (5)$$

where, j is the average rainfall of years, mm/a ; k is the ratio of runoff generation in the total rainfall; r_h is the runoff coefficient of woodland compared with bare land; c_h is the price of headwaters, $\text{US}\$/\text{m}^3$.

(4) Conserving soil value

The soil conservation capacity of forest eco-system mainly reflects on the resisting wind and water erosion. The conserving soil value of woodland, V_w , in $\text{US}\$/\text{hm}^2/\text{a}$, is calculated as:

$$V_w = \frac{y_p}{10000\rho h} v \quad (6)$$

Where, y_p is the soil conservation capacity of woodland, $\text{t}/\text{hm}^2/\text{a}$; ρ is the volume weight of soil, t/m^3 ; h is the thickness of soil, m ; v is the annual profit of some cropland transformed from conserving soil, $\text{US}\$/\text{hm}^2$.

(5) Nutrient cycling value

Nutrient cycling mechanism of woodland forms soil nutrient, containing nitrogen (N), phosphorus (P) and potassium (K). The nutrient cycling value of woodland, V_n , in $\text{US}\$/\text{hm}^2/\text{a}$, is calculated as:

$$V_n = q_f (k_N p_N + f_P k_P p_P + k_K p_K) \quad (7)$$

where, k_N , k_P and k_K are the ratio of N, P and K in the q_f , respectively; p_N , p_P and p_K are the prices of N, P and K, respectively; f_P is the conversion coefficient form P to P_2O_5 .

(6) Total indirect eco-cost estimate.

As model mentioned above, the total indirect eco-cost of woodland damaged by mining, f_{EE} , in $\text{US}\$$, is calculated as:

$$f_{EE} = V_a + V_o + V_h + V_w + V_n \quad (8)$$

The destruction region of mine mainly occurs at stope, refuse dump and tailings pond. According to the state transition in fig.1, the area of $S_{i,j}$ at time I , $A_p(i,j)$, can be measured by the software on the drawing. This area is the damaged area at time i .

The damaged area of refuse dump, $A_w(i, j)$, corresponds to the accumulated volume of stripping rock, $V_w(i, j)$, at time i .

$$A_w(i, j) = \begin{cases} A_{w0} & V_w(i, j) < V_{w0} \\ \frac{H_w - H_{w0}}{V_w - V_{w0}} [V_w(i, j) - V_{w0}] + H_{w0} & V_w(i, j) \geq V_{w0} \end{cases} S_w \quad (9)$$

where, A_{w0} is the leveled area of refuse dump at an early stage, hm^2 ; S_w is the form factor of refuse dump; r_w is the expansion factor of cupped rock; H_w is the height of refuse dump, m; H_{w0} is the initial height of refuse dump, m; V_{w0} is the initial volume of refuse dump, m^3 .

Tailings pond is built one-time for the fluid character of tailings. So, the damaged land of tailings pond occurs at the beginning of mining other than year by year. That is the accumulating damaged area of tailings pond every year is equal to the total damaged area of tailings pond, A_t , in hm^2 .

$$A_t = \frac{Q_t}{\rho_t \cdot H_t} \cdot S_t \quad (10)$$

where, Q_t is the tons of tailings, 10^4t ; S_t is the form factor of tailings pond; ρ_t is the proportion of tailings, t/m^3 ; H_t is the depth of tailings pond, m.

3.4 The carbon emission cost of energy consumption

The impact of energy consumption on the environment mainly reflects in greenhouse gas emission causing global warming. The energy consumption of open pit mining mainly results from stope and dressing plant. Stope mainly consumes diesel, petrol and power (coal) and the carbon emission cost of energy consumption can come down to mining-stripping per unit ton. Dressing plant mainly consumes power and the carbon emission cost of energy consumption can come down to ore dressing per unit ton. So,

the carbon emission cost of stope consuming energy, c_{eo} , in US\$/t, is calculated as:

$$c_{eo} = (e_d f_d + e_g f_g + e_{eo} b a_c f_c) c_c \quad (11)$$

The carbon emission cost of dressing plant consuming energy, c_{do} , in US\$/t, is calculated as:

$$c_{ed} = e_{ed} b a_c f_c c_c \quad (12)$$

where, e_d and e_g are the diesel and petrol consumptions per ton of mined ore or stripped rock, respectively, t/t ; e_{eo} and e_{ed} are the power consumptions per ton of dressed ore, kwh/t ; f_d , f_g and f_c are the carbon emission factor of diesel, petrol and coal, respectively; b is the ratio of using coal in the generating capacity; a_c is the coal consumption to generate a unit of electricity, t/kwh .

The carbon emission cost of energy consumption from $S_{i-1,k}$ at time $i-1$ to $S_{i,j}$ at time i is calculated as:

$$C_c(i, j) = (O_{i,j}(i-1, k) + W_{i,j}(i-1, k)) \cdot c_{eo} + O_{i,j}(i-1, k) \cdot c_{ed} \quad (13)$$

4. Case Study

The algorithm and model built above are applied in a large open pit metal mine, which locates in the north of china. The mine has been mined over years and the remaining reserves are about 0.4 billion tons. The ecological system damaged by mining is mainly deciduous broad-leaved forest. Based on the mining status of stope and related technical and economic parameters of mine, an ultimate pit was optimized with 377.24 million tons of ore and 1061.70 million ton of rock. In the pit, about 315 pushbacks were generated while the increment was 0.25 million tons and the working slope angle was 20° . The technical and economic parameters used to optimize production scheme are set in Table 1. The parameters of calculating ecological costs are set in Table 2. All monetary values are converted to US dollars using an exchange rate of 0.1454 dollar to 1 RMB.

Table 1. The parameters of optimizing mining plan.

Item	Mining cost(US\$/t)	Stripping cost(US\$/t)	Dressing cost(US\$/t)	Concentrate price(US\$/t)	Waste in-ore ratio (%)	Waste grade (%)
value	2.908	1.7448	18.902	82.151	3.5	10
Item	Mining recovery ratio (%)	Dressing recovery ratio (%)	Cutoff grade (%)	Concentrate grade (%)	Rate of cost rise (%)	Rate of price rise (%)
value	95	82	25	66	2	4

Table 2. Parameter values for calculation of ecological costs.

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
$c_z/(\text{US}\$/\text{hm}^2)$	348 960	$c_t/(\text{US}\$/\text{hm}^2)$	58 160	$q_f/(\text{t}/\text{hm}^2/\text{a})$	6.56	λc	1.62
$c_c/(\text{US}\$/\text{t})$	50.59	$y_s/(\text{t}/\text{hm}^2/\text{a})$	0.1521	$c_s/(\text{US}\$/\text{t})$	162.2921	$y_n/(\text{t}/\text{hm}^2/\text{a})$	0.38
$c_n/(\text{US}\$/\text{t})$	2326.4	$y_d/(\text{t}/\text{hm}^2/\text{a})$	21.655	$c_d/(\text{US}\$/\text{t})$	45.9828	$y_g/(\text{t}/\text{hm}^2/\text{a})$	10.95
$c_g/(\text{US}\$/\text{t})$	21.81	y_o	1.2	$c_o/(\text{US}\$/\text{t})$	101.9836	$j/(\text{mm}/\text{a})$	800
k	0.4	r_h	0.26	$c_n/(\text{US}\$/\text{t})$	0.1818	$y_p/(\text{t}/\text{a}/\text{hm}^2)$	60.2915
$\rho/(t/m^3)$	1.3	h/m	0.5	$v/(\text{US}\$/\text{hm}^2)$	3294.118	k_N	4.3×10^{-3}
k_P	3.9×10^{-4}	k_K	2.16×10^{-3}	$p_N/(\text{US}\$/\text{t})$	319.88	$p_P/(\text{US}\$/\text{t})$	94.51
$p_K/(\text{US}\$/\text{t})$	328.4586	f_P	2.2903	S_w	1.5	r_w	1.25
H_w/m	150	H_{w0}/m	40	$V_{w0}/(\text{m}^3)$	200×10^4	S_t	1.5
$\rho_t/(\text{t}/\text{m}^3)$	1.75	H_t/m	100	$e_d/(\text{t}/\text{t})$	5.664×10^{-4}	$e_g/(\text{t}/\text{t})$	4.1×10^{-6}
$e_{col}/(\text{kWh}/\text{t})$	1.2	$e_{ed}/(\text{kWh}/\text{t})$	28.5	f_d	3.1865	f_g	3.1309
f_c	2.7335	b	0.8	$a_c/(\text{t}/\text{kWh})$	4.04×10^{-4}		

Based on the parameters set above, capital construction and closing period are set as one year and two years, separately. The land acquisitions of stope and tailings pond are finished in the initial stage of mining, while refuse dump are two phases. The first phase occurs in the initial stage of mining and the volume is 0.25billion m³. The second phase occurs in the previous year that the first refuse dump

finished dumping. Reclamation occurs in three years after mine closed and the reclamation areas of each year are equal. The indirect eco-cost will last for five years after mine closed. The results of production scheme optimization and the eco-costs of each production scheme are listed in Table 3.

Table 3. Production scheduling and ecological costs of schemes.

year	Scheme I				Scheme II				Scheme III			
	ore /10 ⁴ t	Waste /10 ⁴ m ³	NPV/10 ⁶ US\$	Eco-cost /10 ⁶ US\$	ore /10 ⁴ t	Waste /10 ⁴ m ³	NPV/10 ⁶ US\$	Eco-cost /10 ⁶ US\$	ore /10 ⁴ t	Waste /10 ⁴ m ³	NPV/10 ⁶ US\$	Eco-cost /10 ⁶ US\$
1	7.47	20.41	0.44	339.28	7.47	20.41	0.44	339.28	7.47	20.41	0.44	339.28
2	1306.63	428.42	118.53	18.78	1306.63	428.42	118.53	18.78	1306.63	428.42	118.53	18.78
3	1410.41	4410.14	68.67	24.23	1291.46	4007.06	63.12	22.23	1291.46	4007.06	63.12	22.23
4	1302.08	4607.97	58.42	22.42	1302.19	4591.76	59.37	22.38	1302.19	4591.76	59.37	22.38
5	1305.03	4572.24	62.92	21.51	1305.5	4539.3	62.77	21.46	1305.5	4539.3	62.77	21.46
...	...	...	...	...	...	...	...	...	...	...	...	...
22	1662.6	3026.98	128.17	11.24	1663.23	3131.21	127.58	11.29	1664.24	3264.59	126.74	11.37
23	1661.66	2605.85	130.7	10.51	1661.23	2633.11	130.32	10.52	1660.43	2649.25	130.27	10.52
24	1663.4	1817.11	133.82	9.66	1663.01	1887.39	133.33	9.69	1663.47	1945.8	133.05	9.72
25	1661.74	1271.25	137.23	8.97	1662.38	1270.97	137.39	8.97	1662.25	1283.55	136.88	8.97
26	1660.26	1625.04	134.87	8.69	1660.42	1546.34	134.93	8.66	1660.56	1496.83	135.27	8.64
27					118.23	182.75	9.32	1.7	118.48	141.02	9.39	1.68
28									118.23	182.75	9.2	1.62
			2450.76	916.31			2453.25	914.94			2453.10	914.48
total	37137.35	106756.2	Comprehensive profit: 1534.45		37137.35	106756.2	Comprehensive profit: 1538.31		37137.35	106756.2	Comprehensive profit: 1538.62	

Note: the indirect eco-costs in five years after mine closed are not listed in table 3 while considered in total.

In Table 3, there are top three NPV of production schemes, Scheme I, Scheme II and Scheme III. It can be seen, ore-rock tons of different schemes of each year are diverse and the eco-cost in each year are different as well. Without eco-costs, the maximum NPV of three schemes is Scheme II, whose mining life is 27 years and the NPV is 2453.25×10^6 US\$. With eco-cost, the maximum NPV is Scheme III, whose mining life is 28 years and the comprehensive profit is 1538.62×10^6 US\$. The comprehensive profit of Scheme III is more than Scheme II, is 0.31×10^6 US\$. Different production schemes has different eco-costs which has an impact on choosing scheme.

5. Conclusions

Combining production character of mine, the model of calculating eco-cost is built to quantify environment issues caused by resource mining. Top three NPV of production schemes are optimized in the ultimate pit and the eco-costs of different scheme are calculated. It is shown that different scheme leads to different ecological costs. Without eco-costs, the optimum production scheme is Scheme II whose NPV is maximum. With eco-costs, the optimum production scheme is Scheme III which comprehensive is maximum. It is ecological costs that has an impact on choosing production scheme, if environmental issues would be taken into account.

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