OPTIMIZATION OF BLENDING OPERATION FOR ASWAN PHOSPHATE MINES USING LINEAR PROGRAMMING

Mahrous A.M. Ali1*, H.S. Wasly1, W.R. Abdellah2, Hyongdoo Jang3
1Al-Azhar University, Qena, Egypt
2Assiut University, Assiut, Egypt
3Curtin University, Perth, Australia
*Corresponding author: e-mail mahrous_mining@yahoo.co.uk, tel. +20963210223, fax: +20963210223

ABSTRACT

Purpose. The economic value of phosphate is reduced when randomly blending raw phosphate produced from different mines. Therefore, the blending process of different raw phosphate ores to produce economic percentage of P2O5 is essential to maximize the profit of a mine.

Methods. This paper presents an application of Linear programming (LP) method to determine the optimum quantities of phosphate ore needed per each mine for blending process. Three phosphate operations, located in Aswan province south of Egypt, have been chosen for this study namely B1, B2 and C.

Findings. The results of LP methods reveal that the phosphate ore of 24% of P2O5 will be produced by blending 16.8% of phosphate ore from operation B1, 9.42% of phosphate ore from operation B2 and 73.78% of phosphate ore from operation C. Whilst the phosphate ore of 22% P2O5 will only be obtained by blending 66.43% of phosphate ore from operation B1 and 33.57% from mine B2.

Originality. Using the linear programming by applying solver function in mine operations.

Practical implications. Applied linear programming in mining as regard mining operations to obtain the optimum solution in mining sites.

Keywords: linear programming, blending operation, profit optimization, phosphate ore deposit

1. INTRODUCTION

Phosphate is a non-detrital sedimentary rock which contains high amounts of phosphate bearing minerals, where considering the phosphorite rock (e.g. calcium phosphate) comprises only 15 – 20% of phosphate. The content of phosphate in the phosphorite rock would vary upon the contents of hydroxyapatite and fluoroapatite. For example, if the phosphorite rock contains 20% of these primary minerals, then the percentage of phosphorous will be 18.5%. On the other hands, comparing with the typical sedimentary rock, which consists less than 0.2% of phosphorous, the phosphorite rock is considered as a phosphorous enriched mineral as well, when it contains more than 3.7% phosphorous (McClellan, 1980).

The total phosphate production of the world is 137 million tons annually, 28.1% have been produced by United States (40.87 million tons), 21.1% China (30.75 million tons), and 15.1% Morocco (22 million tons). The rest of phosphate is produced from various countries, such as Brazil, Russia, Jordan, and Tunisia.

Phosphate is one of the common ore deposits in Egypt as it extends to a distance of 750 km from the coast of Red Sea in the east to the west of Dakhla Oasis (Stowasser, 1983).

1.1. Study area

Most of sedimentary deposits are formed in offshore marine conditions on the continental shelves. Such deposits are exhibited in a wide variation in the chemical composition and physical nature. Phosphate rocks contain distinct phosphate particles that can be separated from the unwanted gangue minerals. Insular deposits (e.g. a type of sedimentary deposit that associated with oceanic islands) have been considered as the main source of phosphate rocks for more than hundred years.

However, most of these deposits are totally depleted. From economic point of view, the valuable phosphate in Egypt is located in three main areas. The first locations are called Sibaiya and Mahameed where are part of Nile Valley (in between Idfu and Qena). The geological reserve of phosphate ore in this region is estimated by 200 million tons in Mahameed only, where the percen-
tage of phosphorous oxide is 22%. The second place of phosphate ore is located between Sagafa and Quseir (e.g. Mount Dawi, Thirsty and Hamrawein) (Said, 1962; Issawi, 1968; Dabous, 1980). The estimated phosphate reserve in this area is 200 – 250 million tons where P₂O₅ ranges from 27 to 30%. Abu-Tartur is the third place which is one of the largest phosphate deposits existed in Egypt. The estimated phosphate reserve in this area is 1 billion tons where P₂O₅ is 25%. Although the percentage of P₂O₅ ranges between 22 and 30% in the Egyptian phosphate, however, production is very costly due to the proportion of impurities.

In the present study, nine samples of phosphate rocks have been obtained from three operations named B1, B2, and C of El-Gera mines located in Aswan, south of Egypt. The studied area lies between latitudes 32°34′44.9″ North, bearing 45°, Longitude 25°10′48.8″ and at 4-kilometer west of Idfu, Aswan Governorate (Issawi, 1979). The location map of the study area is shown in Figure 1 and the stratigraphic column of the phosphate deposit is shown in Figure 2. Table 1 lists the surface geological reserve of phosphate ore and percentage of P₂O₅ in the three operations. To maximize the profit of El-Gera mine, optimizations of a blending process of phosphates produced from the three operations and optimum height of a bench design are essential.

1.2. Estimating phosphate reserve

In this study, ore reserves estimation are calculated according to the borehole data by using statistical calculations, volume and total amounts of ore reserves based on the thickness of boreholes, assay and topographic information of the study operations of B1, B2 and C. Each location of the study area is classified into upper, lower and third strata. Table 2 gives the estimated surface geological reserve of phosphate ore in the three operations and the life of the mine has been determined (David, 1977; Hustrulid & Kuchta, 1995).

1.3. Mine design and planning

Several factors affect the design of open pit such as geometry (e.g. size and shape), characteristics of ore/rock mass (e.g. strength properties, ore extent/dip angle, cut-
off grade, etc.), design parameters (e.g., height of bench, slope angle, berm, etc.) and operational costs (e.g., cost of extraction, milling/processing, transportation, storage, market prices, etc.) (Hustrulid, Kuchta, & Martin, 2006; Adilson, Marcos, Wilson, & Valdir, 2013; Aitsebaomo, Ngerebara, Teme, & Ngah, 2015).

Height of the bench is considered as one of the prominent parameters that have a great effect on the overall mine profit. It is defined as the vertical distance between two horizontal levels of open pit. It could be fixed for all benches unless the geologic conditions dictate otherwise, such as height should be designed according to characteristics of ore deposit, degree of selectivity, size of equipment, climatic conditions and rate of productions (Ulusay, 2014). In large phosphate mines, height of bench normally varies from 12 to 20 m and is divided into sub-benches. Figure 3 demonstrates a sectional view of a bench in the operations B1, where the heights of overburden, third, upper and lower layers are 7, 0.2, 0.41 and 0.38 m respectively.

Table 3 gives the characteristics of phosphate ore deposits in the three operations, while Table 4 illustrates the calculated height of benches using various formulas in accordance with slope stability, safety and efficiency of work place.

### Table 3. The physical and mechanical properties of the tested phosphate samples

<table>
<thead>
<tr>
<th>Location</th>
<th>$\sigma_c$, t/m$^2$</th>
<th>$T_s$, kg/cm$^2$</th>
<th>Density, gm/cm$^3$</th>
<th>Water absorption, %</th>
<th>Internal friction, deg.</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>104.3</td>
<td>65</td>
<td>1.97</td>
<td>16.4</td>
<td>30</td>
<td>All data calculated</td>
</tr>
<tr>
<td>B2</td>
<td>120.6</td>
<td>50</td>
<td>2.20</td>
<td>12.8</td>
<td>29</td>
<td>using statistical analysis</td>
</tr>
<tr>
<td>C</td>
<td>117.8</td>
<td>75</td>
<td>2.15</td>
<td>13.7</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4. Calculated height of bench for the three phosphate operations

<table>
<thead>
<tr>
<th>Methods</th>
<th>Equation</th>
<th>Bench height, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>$H = \frac{C}{\delta \sin 2\alpha}$</td>
<td>131.9 90.9 139.53</td>
</tr>
<tr>
<td>A-2</td>
<td>$H = 0.985 \cdot \frac{C}{\delta}$</td>
<td>126.4 87.09 133.67</td>
</tr>
<tr>
<td>A-3</td>
<td>$H_c = 2 \cdot C \cdot \frac{\cos \phi}{\delta (1 - \sin \phi)}$</td>
<td>126.4 87.09 133.67</td>
</tr>
<tr>
<td>A-4</td>
<td>$H = \frac{\sigma_c}{\delta}$</td>
<td>131.8 65.76 109.55</td>
</tr>
<tr>
<td>B</td>
<td>$H = 1.5 \cdot H_{d_{\text{max}}}$</td>
<td>52.9 54.81 54.79</td>
</tr>
<tr>
<td>C</td>
<td>$H = 0.7^a \frac{\sin \alpha \sin \beta}{k \xi (1 + \xi')} \sin (\beta - \alpha)$</td>
<td>30.75 30.75 30.75</td>
</tr>
</tbody>
</table>

*Note: A – bench height calculation considering slope stability; A-1 – N.A. Tsykevich; A-2 – Fellenius modified; A-3 – V.V. Sokovsky; A-4 – E.M. Demen; B – bench height calculation due to safety of work place; C – bench height calculation due to the efficiency of work place; $H_{d_{\text{max}}}$ – maximum digging height of the excavator, m; $a = 0.8(R_d + R_l)$, where $a$ is a width of the broken down heap of materials formed after blasting, m; $\alpha$ – slope angle of broken down materials, deg. (e.g., for phosphate $\alpha = 3^\circ$); $\beta$ – slope angle of the face, deg.; $k$ – loosening factor of the face material (coefficient of swelling); $\xi$ – ratio of length of least resistance line of first row of blast holes face height, usually, equal to 0.55 – 0.70; $\xi'$ – ratio of distance between rows of blast holes to length of line of least resistance, usually, equal to 0.75 – 0.80; $R_d$ – digging radius of power shovel, m; $R_l$ – loading radius of power shovel, m.*
2. BLENDING OPERATION

This study is adapted to three phosphate operations (e.g. B1, B2, and C) located in the Nile Valley, El-Sibaiya west area. The three operations have variations in amount of phosphate reserve and assay. Consequently, some assays may become waste (when P₂O₅ percentage is beyond the economic value 20% P₂O₅ and cannot compete with global market. Therefore, improving the poor assays by blending phosphate ores is essential to maximize profit of the mine. To determine the optimum quantities of phosphate ore per each mine to optimize profit, LP has been applied Figure 4 depicts the stages of blending operation. The ore is prepared in the first stage using a front-end loader then it is fed to blending plants in the second stage.

![Figure 4. Stages of blending operation](image)

Phosphate rocks widely vary in both chemical composition and the nature of associated principle minerals. Therefore, the big concern in phosphate ore production is blending operation (Ashayeri, van Eijs, & Nederstigt, 1994; Shih & Frey, 1995; El-Arabi & Khalifa, 2002; Gholamnejad & Kasmaee, 2012; Song, Hu, & Li, 2012). Spectrophotometric technique has been used to analyze the chemical composition of phosphate rocks at chemical labs of Nile Valley Company as listed in Table 5. The chemical analysis reveals that the most oxides are existed in phosphate rocks are SiO₂, Al₂O₃, TiO₂, and P₂O₅. Table 6 gives the quantities and assays of phosphate rock per each mine. Table 7 displays the selling prices of phosphate ore based on its P₂O₅ percentage.

### Table 5. Chemical composition of the phosphate rocks obtained from three operations

<table>
<thead>
<tr>
<th>Element, %</th>
<th>B1</th>
<th>B2</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₂O₅</td>
<td>30.4</td>
<td>29.3</td>
<td>25</td>
</tr>
<tr>
<td>CaO</td>
<td>48 – 49</td>
<td>47 – 48</td>
<td>44 – 45</td>
</tr>
<tr>
<td>MgO</td>
<td>0.3 – 0.4</td>
<td>0.3 – 0.5</td>
<td>0.3 – 0.5</td>
</tr>
<tr>
<td>Fe₂O₅</td>
<td>1.8 – 2.1</td>
<td>1.8 – 2.0</td>
<td>1.8 – 2.0</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.2 – 0.7</td>
<td>0.5 – 0.8</td>
<td>0.5 – 1.0</td>
</tr>
<tr>
<td>SiO₂</td>
<td>6 – 7</td>
<td>8 – 9</td>
<td>12 – 15</td>
</tr>
<tr>
<td>SO</td>
<td>1.5 – 1.8</td>
<td>1.5 – 1.8</td>
<td>1.5 – 1.8</td>
</tr>
<tr>
<td>Cl</td>
<td>0.03 – 0.06</td>
<td>0.03 – 0.07</td>
<td>0.08 – 0.1</td>
</tr>
<tr>
<td>F</td>
<td>3.0 – 3.1</td>
<td>2.9 – 3.0</td>
<td>2.5 – 2.7</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.3 – 0.5</td>
<td>0.3 – 0.5</td>
<td>0.3 – 0.5</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.02 – 0.06</td>
<td>0.02 – 0.06</td>
<td>0.05 – 0.1</td>
</tr>
<tr>
<td>LOI</td>
<td>6.5 – 7.5</td>
<td>7 – 8</td>
<td>9 – 11</td>
</tr>
<tr>
<td>CO₂</td>
<td>4.5 – 5.5</td>
<td>5 – 6</td>
<td>7 – 9</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>10.2 – 12.5</td>
<td>11.3 – 13.6</td>
<td>15.9 – 20.4</td>
</tr>
</tbody>
</table>

### Table 6. The quantities and assays of phosphate ore per each mine

<table>
<thead>
<tr>
<th>Operation</th>
<th>Quantities, ton</th>
<th>Average assay, P₂O₅%</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>215311</td>
<td>23.6</td>
</tr>
<tr>
<td>Lower</td>
<td>192096</td>
<td>23.6</td>
</tr>
<tr>
<td>B2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>112374</td>
<td>23.5</td>
</tr>
<tr>
<td>Lower</td>
<td>132127</td>
<td>24.3</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>801150</td>
<td>24.0</td>
</tr>
<tr>
<td>Lower</td>
<td>1115627</td>
<td>24.2</td>
</tr>
<tr>
<td>Total</td>
<td>2655527</td>
<td></td>
</tr>
</tbody>
</table>

### Table 7. The selling price of phosphate ore according to assay in global market 2016

<table>
<thead>
<tr>
<th>Assay, P₂O₅%</th>
<th>Selling price, $/ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>15.5</td>
</tr>
<tr>
<td>23</td>
<td>12.5</td>
</tr>
<tr>
<td>22</td>
<td>10.5</td>
</tr>
<tr>
<td>21</td>
<td>5.0</td>
</tr>
</tbody>
</table>

3. NUMERICAL METHODOLOGY

The first step is to define the decision variables, \(X_i\). Where variable \(i\) refers to amount of phosphate ore excavated from operation B1, B2 and C. The second variable, \(j\) denotes to P₂O₅ assay (e.g. 21, 22, 23 and 24%). Then, the objective function, that maximizes the profit contribution, can be developed by multiplying the selling price and quantities of the phosphate ores, as illustrated by Equation 1:

\[
\text{max} 15.5(x_{11} + x_{21} + x_{31} + x_{41} + x_{51} + x_{61} + x_{71} + x_{81}) +
12.5(x_{12} + x_{22} + x_{32} + x_{42} + x_{52} + x_{62} + x_{72} + x_{82}) +
10.5(x_{13} + x_{23} + x_{33} + x_{43} + x_{53} + x_{63} + x_{73} + x_{83}) +
5(x_{14} + x_{24} + x_{34} + x_{44} + x_{54} + x_{64} + x_{74} + x_{84}).
\]

Equations 2 to 9 are given the constraints should be achieved to attain maximum profit and satisfy the entire product specifications:

\[
x_{11} + x_{12} + x_{13} + x_{14} \leq 67.400; \quad (2)
\]
\[
x_{21} + x_{22} + x_{23} + x_{24} \leq 215.311; \quad (3)
\]
\[
x_{31} + x_{32} + x_{33} + x_{34} \leq 192.096; \quad (4)
\]
\[
x_{41} + x_{42} + x_{43} + x_{44} \leq 19.441; \quad (5)
\]
\[
x_{51} + x_{52} + x_{53} + x_{54} \leq 112.374; \quad (6)
\]
\[
x_{61} + x_{62} + x_{63} + x_{64} \leq 132.127; \quad (7)
\]
\[
x_{71} + x_{72} + x_{73} + x_{74} \leq 801.150; \quad (8)
\]
\[
x_{81} + x_{82} + x_{83} + x_{84} \leq 1115.627. \quad (9)
\]

Amount of phosphate is blended must be equal to number of targeted assays, as given per Equations 11 to 16:

\[
22.5x_{11} + 23.6x_{21} + 23.6x_{31} + 21.8x_{41} + 23.5x_{51} +
24.3x_{61} + 24.3x_{71} + 24.2x_{81} = 24(x_{11} + x_{21}) +
+x_{31} + x_{41} + x_{51} + x_{61} + x_{71} + x_{81}; \quad (10)
\]
22.5x_{12} + 23.6x_{22} + 23.6x_{32} + 21x_{42} + 23.5x_{52} + $\frac{+24.3x_{62} + 24x_{72} + 24.2x_{82}}{23} = 23(x_{12} + x_{22} + $\frac{+x_{32} + x_{42} + x_{52} + x_{62} + x_{72} + x_{82}}{23}$);

22.5x_{13} + 23.6x_{23} + 23.6x_{33} + 21x_{43} + 23.5x_{53} + $\frac{+24.3x_{63} + 24x_{73} + 24.2x_{83}}{22} = 22(x_{13} + x_{23} + $\frac{+x_{33} + x_{43} + x_{53} + x_{63} + x_{73} + x_{83}}{22}$);

22.5x_{14} + 23.6x_{24} + 23.6x_{34} + 21x_{44} + 23.5x_{54} + $\frac{+24.3x_{64} + 24x_{74} + 24.2x_{84}}{21} = 21(x_{14} + x_{24} + $\frac{+x_{34} + x_{44} + x_{54} + x_{64} + x_{74} + x_{84}}{21}$);

(Non-negative) $\sum x_{ij} \geq 0$; (14)

$\sum x_{ij} =$ Total quantities of phosphate ores in 3 mines. (15)

3.1. Spreadsheet model and solver implementation

To implement the problem into excel spreadsheet; the following parameters should be included:

a) cells E4 to H11 represent the twelve decision variables (e.g. according to selling assays) and the cell A30 represents the objective function;

b) cells C15 to C27 represent the constraints left-hand sides and cells D15 to D27 represent the constraints right-hand sides as shown in Figure 5;

c) non-negativity constraints are not implemented in the spreadsheet and can be implemented in the solver.

The complete set of constraints, target cell (e.g. objective function cell); variable cells and whether to maximize or minimize the objective function are identified in the solver parameters box as shown in Figure 6. While, the optimal distribution of phosphate ores in the blending operation is shown in Figure 7. Cell (A30) gives the optimal solution for the objective function.

4. RESULTS

The demonstrated LP allows exploiting all quantities of phosphate ore from the three mines. Blending operation can be done on daily, weekly and shift bases. The results of the proposed solution are converted to percentages since the blending process cannot be done at equal daily portions during the life of the mine.

Some technical problems may rise and affect the production rate and blending process. Figure 8 shows the percentages of phosphate assay after blending process using LP. Blending plant may be built in the crusher location where topographic conditions are suitable. Table 8 summarizes the results of the obtained optimal solution for the blending operation.
and upper layers respectively) from mine B1 and 33.57% phosphate of 66.43% (e.g. 66.10 and 0.33% from third and lower layer respectively) from mine C. While, phosphate rock B2, and 73.79% (e.g. 30.84 and 42.95% from upper 5.09% from upper and lower layers respectively) from mine B2. Many changes have been applied to the technology satisfies all constraints.

5. CONCLUSIONS
Optimization of ore blending operation is crucial to maximize the profit of a phosphate mine. Such optimization requires investigating the physical and mechanical properties of ore, estimating ore reserve and achieving optimal quantity of ores to be blended together. Nine phosphate rocks have been collected from three operations named B1, B2 and C located in Aswan governorate, south of Egypt. Triangular method has been used to estimate ore reserves in the three operations and LP technique is adopted to determine the optimum quantities of phosphate per each mine to obtain economic assay. The results reveal that the phosphate ore of 24% of P2O5 will be obtained when blending phosphate quantity of 16.8% (e.g. 1.12, 8.28 and 7.40% from third, upper and lower layers respectively) from mine B1, 9.42% (e.g. 4.53 and 5.09% from upper and lower layers respectively) from mine B2, and 73.79% (e.g. 30.84 and 42.95% from upper and lower layer respectively) from mine C. While, phosphate ore of 22% of P2O5 will be produced when blend phosphate of 66.43% (e.g. 66.10 and 0.33% from third and upper layers respectively) from mine B1 and 33.57% from mine B2. Many changes have been applied to the given solution to check the optimum quantity of blending operation. Thus, the empty cells in the spreadsheet will be occupied by 1 ton of phosphate ore from different locations and used to determine the new objective function. Such function will be compared with the first objective function. It is noteworthy that the optimum blending solution is only reached when maximum objective function satisfies all constraints.

ACKNOWLEDGEMENTS
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Table 8. Summary of the optimal solution for the blending process

<table>
<thead>
<tr>
<th>Mine</th>
<th>Layer</th>
<th>Blending percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>24%</td>
</tr>
<tr>
<td>B1</td>
<td>Third</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>Upper</td>
<td>8.28</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>7.40</td>
</tr>
<tr>
<td>B2</td>
<td>Third</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Upper</td>
<td>4.33</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>5.09</td>
</tr>
<tr>
<td>C</td>
<td>Upper</td>
<td>30.84</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>42.95</td>
</tr>
</tbody>
</table>
OPTIMIZATION OPERATIONS OF MIXING ON ASUAN PHOSPHATE MINE SITES WITH LINEAR PROGRAMMING


ОПТИМАЛІЗАЦІЯ ОПЕРАЦІЙ ЗМІШУВАННЯ
НА АСУАНСЬКИХ ФОСФАТНИХ РУДНИКАХ
ІЗ ВИКОРИСТАННЯМ ЛІНЕЙНОГО ПРОГРАМУВАННЯ

Магроус А.М. Алі, Х.С. Васлі, В.Р. Адбеллах, Хіонгду Джанг

Мета. Оптимізація операцій змішування фосфатних руд, що добуваються з трьох різних рудників родовища фосфатів (провінція Асуан), на основі використання лінійного програмування для максимізації прибутку гірничого підприємства.

Методика. У роботі використано метод лінійного програмування (ЛП) для визначення оптимальної кількості фосфатної руди в процесі змішування, видобутої рудниками на різних ділянках родовища. Для цього розглянуто три рудники, що розташовані на різних ділянках родовища. Для експерименту відібрано три зразки фосфатної руди з кожного рудника, що стадійно перемішувались згідно розробленої схеми. Хімічний склад фосфатних порід, що добуваються з трьох ділянок родовища, визначався спектрофотометричним аналізом.

Результати. В процесі лінійного програмування складена целевая функція з урахуванням відпускної ціни та кількості фосфатних руд певного вмісту P2O5, що максимізує прибуток. Виявлено, що у результаті змішування фосфатних руд, добуваних рудниками на різних ділянках родовища, встановлено, що економічна цінність фосфату зменшується при випадковому змішуванні сирьовини, видобутої на різних рудниках.

Наукова новизна. Вперше для умов фосфатних рудників Ель-Гера (провінція Асуан) застосовано метод лінійного програмування для оптимізації якості фосфатної руди, що дозволило максимізувати прибуток гірничого підприємства.

Практична значимість. Прикладне використання лінійного програмування в гірничій справі дозволяє піднімати якість видобутої фосфатної руди з різних ділянок родовища провінції Асуан та підвищити її конкурентоспроможність на світовому ринку.

Ключові слова: лінійне програмування, операція змішування, оптимізація прибутку, родовище фосфатної руди

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ABOUT AUTHORS

Mahrous A.M. Ali, Doctor of Philosophy, Assistant Professor of the Mining and Petroleum Engineering Department, Al-Azhar University, Maskan Osman, 83215, Qena, Egypt. E-mail: mahrous.mining@yahoo.co.uk

Hamdy S. Wasly, Doctor of Philosophy, Assistant Professor of the Mining and Petroleum Engineering Department, Al-Azhar University, Maskan Osman, 83215, Qena, Egypt. E-mail: elwasly_hs@yahoo.com

Wael Rashad Abdellah, Doctor of Philosophy, Assistant Professor of the Mining and Metallurgical Engineering Department, Assiut University, 71516, Assiut, Egypt. E-mail: wre544@gmail.com

Hyongdoo Jang, Doctor of Philosophy, Associate Professor of the Western Australian School of Mines, Science and Engineering, Curtin University, Kent Street, Bentley, WA 6102, Perth, Australia. E-mail: hyongdoo.jang@curtin.edu.au