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MATHEMATICAL MODEL FOR OPTIMAL TRANSPORTATION SYSTEM SELECTION IN UNDERGROUND METAL MINES

MATEMATIČKI MODEL ZA IZBOR OPTIMALNOG TRANSPORTNOG SISTEMA U PODZEMNIM RUDNICIMA METALA

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Abstract: *The paper propose complex mathematical model for transportation system selection through the main transportation drifts in underground metal mines. Multi-criteria decision making methods are used for selection of optimal transportation system during the designing phase. Beside minimal specific transportation costs, the multi - criteria method includes other criteria, which are meaningful for transportation system selection.*

Key words: *transportation system, specific transportation costs, technico-economic analysis, and multi-criteria analysis*

Apstrakt: *U radu je predstavljen kompleksan matematički model za izbor transportnog sistema u glavnim transportnim prostorijama u rudnicima za metalične mineralne sirovine sa podzemnom eksploatacijom.Primenjene su metode za višekriterijumsko odlučivanje za izbor optimalnog transportnog sistema u fazi proektovanja. U metodu višekriterijumske analize pored kriterijuma za minimalne specifične transportne troškove korišćeni su i drugi kriterijumi koji su bitni za izbor transportnog sistema.*

ključne reči: *transportni sistem, specifični transportni troškovi, tehničko-ekonomska analiza, višekriterijumsko odlučivanje*

1 INTRODUCTION

Main transportation drifts are capital mine workings which connect hoisting shafts with mineral processing plants on the surface, or central ore passes with main hoisting shafts. The transportation of ore through these drifts could be done by various transportation systems, like rails or truck.

This is way the complex analysis of possible solutions is necessary in order to select optimal transportation system. Very often this is time-

1 UVOD

U rudnicima sa podzemnom eksploatacijom glavne transportne prostorije su kapitalni rudarski objekti koji povezuju glavna izvozna okna u jami i objekte za pripremu mineralnih sirovina na površini ili centralne rudne sipke i glavna izvozna okna. Transport rude može da se vrši sa različitim transportnim sistemima, a najčešće se koristi: lokomotivski, trakasti i kamionski transport.

Izboru transportnog sistema treba da prethodi kompleksna analiza mogućih rešenja, pri čemu consuming work, which need wide spectrum of knowledge for transportation means and systems. Additionally criteria accepting in decision-making process are very difficult task. Until recently the most used criterion for decision-making was minimal specific transportation costs. But the obtaining of optimal solution of the problem based on this criterion only is not possible, because the other elements meaningful for right solutions are not included.

The paper propose a mathematical model, where beside technico-economic analysis a multi criteria analysis is included in selection of optimal transportation system. Beside the minimal specific costs, the multi – criteria analysis includes: capital investment costs, manpower requirements, safety, underground atmosphere pollution, reliability and automation possibilities of the system. These complex analyses of transportations systems provide us opportunity to select the optimal solution for given conditions. The methodology proposed is used for transportation system selection in SASA mine.

2 METHODOLOGY FOR OPTIMAL TRANSPORTATION SYSTEM SELECTION

In order to design a transportation system in main transportation drifts, a general model development is needed. The general model structure is presented on the figure that follows.

The figure shows that two types of analyses are used in transportation system selection (Grujic, [4]):

- Techico –economic
- Multi – criteria

treba da se razradi veći broj mogućih varijanti. Ovo je dug i skup proces i zahteva dobro poznavanje širokog spektra transportnih sredstava i uređaja. Kao dodatni problem prilikom izbora transportnog sistema u glavnim transportnim prostorijama javlja se problem usvajanja kriterijuma za odlučivanje od strane lica koje treba da donese odluku. Do sada je najčešće korišćen kriterijum minimalnih specifičnih transportnih troškova. Međutim, za egzaktno rešavanje problema ovaj kriterijum nije dovoljan jer ne uzima u obzir sve elemente koji su značajni za donošenje pravilne odluke.

U ovom radu je predložen matematički model gde se pored tehničko-ekonomske analize uvodi i višekriterijumska analiza za izbor optimalnog transportnog sistema. Višekriterijumska analiza pored minimalnih specifičnih transportnih troškova kao kriterijum za odlučivanje uključuje i: visinu ukupnih investicija, strukturu radne snage, bezbednost sistema, zagađivanje jamskih prostorija, pouzdanost i mogućnosti automatizacije transportnog sistema. Ova kompleksna analiza transportnih sistema omogućava izbor optimalnog rešenja pri datim uslovima. Predložena metodologija je proverena pri izboru transportnog sistema u uslovima rudnika za olovo i cink Sasa.

2 METODOLOGIJA IZBORA OPTIMALNOG TRANSPORTNOG SISTEMA

Za projektovanje transportnog sistema u glavnim horizontalnim prostorijama neophodno je da se uradi opšti matematički model, čija struktura je data na slici 1.

Od gornje slike sleduje da za izbor transportnog sistema u glavnim rudarskim prostorijama postoje dve vrste analize (Grujić, [4]):

- tehničko-ekonomska i
- višekriterijumska analiza.

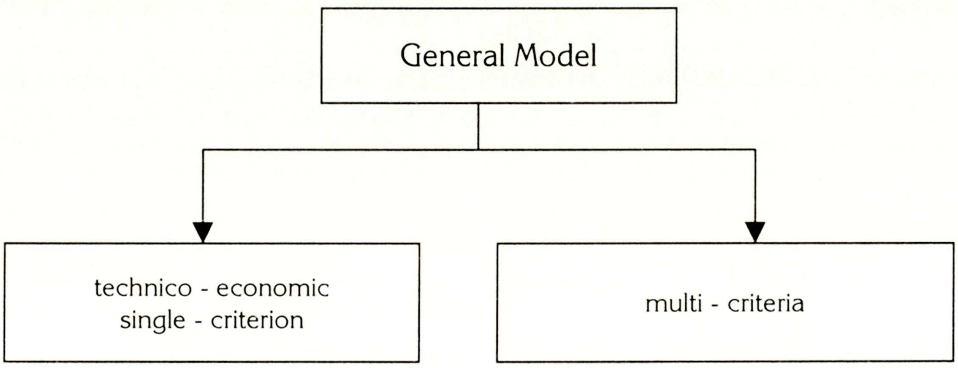

Figure 1 General model for transportation system selection

slika 1 Struktura opšteg modela za izbor transportnog sistema u glavnim transportnim prostorijama

Results obtained with technico-economic analysis are used in multi criteria through the minimal specific transportation costs criterion. This model gives us possibility toe compare large number of different options with different transportation systems or different options within same transportation system. The paper analyses electric powered locomotive, battery powered locomotive and conveyor belt systems. Anyway the model is open for other systems (like trucks transportation) to be included.

2.1 Techico –economic analysis

Ability of modern computing machines to store a large amount of data for transportation systems give us opportunity to build a model for optimal transportation system selection. The data for each transportation mean are organized according the specific criteria and arranged in matrices or databases by specific principles for each parameter. After the data for each means, systems and objects are collected, a rationalization process is conducted. After this an economic parameters of transportation means are added, organized according the same criteria. With this, the model is ready for comparing of transportation systems. The algorithm of sub model for transportation system selection with technico- economic analysis by minimal specific transportation costs criterion is illustrated on figure 2.

Rezultati koji su dobijeni primenom tehničko--ekonomske analize se koriste u višekriterijumskoj analizi preko kriterijuma za minimalne specifične transportne troškove. Ovaj model omogućava upoređivanje većeg broja varijanti transportnih sredstava i to istog i različitog vida transportnih sredstava. U ovom radu su analizirani: lokomotivski transportni sistem sa trolej lokomotivama, lokomotivski transportni sistem sa akumulatorskim lokomotivama i trakasti transportni sistem. Pored ovih transportnih sistema u model može da bude uključen i kamionski transportni sistem.

2.1 Tehničko-ekonomska analiza

Sposobnost savremenih računarskih sistema da memoriraju veliku količinu podataka za transportne sisteme daje mogućnost za formiranje modela za izbor optimalnog transportnog sistema. Podaci o svakom transportnom sredstvu se sistematiziraju prema određenom kriterijumu i grupšu se tako da se formiraju matrice podataka ili baze podataka prema utvrđenim principima za svaki parametar. Posle sakupljanja podataka za sva transportna sredstva, uređaje i objekte neophodno je da se pristupi ka njihovoj racionalizaciji, odnosno utvrđivanju oblasti gde je njihova primena moguća i realna. Tako racionaliziranim podacima dodaju se i ekonomski parametri transportnih sredstava koji su uređeni po istim kriterijumima. Time je model pripremljen za funkcionisanje, odnosno za upoređivanje transportnih sistema. Na slici 2 je prikazan algoritam podmodela za izbor transportnog sistema sa tehničko-ekonomskom analizom prema kriterijumu za minimalne specifične transportne troškove.

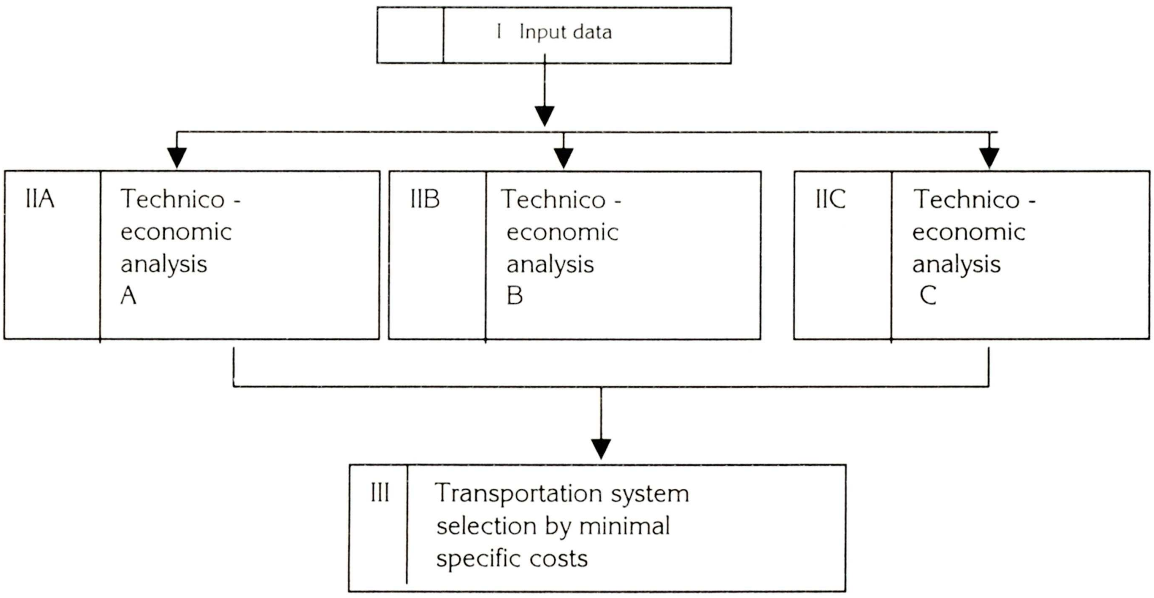

Figure 2 Sub model algorithm for transportation system selection by technico-economic analysis
slika 2 Algoritam podmodela za izbor transportnog sistema pomoću tehničko-ekonomske analize

The previous figure shows the three blocks of the algorithm:

- Input blocks,
- Technico – economic analysis block and
- Optimal solution selection block.

The detailed description of the blocks follows:

Block I. The common input data for transportation systems are gathered herein:

- Annual ore production, $Q_y(t)$
- Transportation length, L(m)
- Average inclination of transportation drift, $\alpha(^\circ)$
- Capacity reserve coefficient, k_1
- Bulk ore mass, γ_r (t/m^3)
- The transportation system lifetime, T (years)
- Number of working days per year, z
- Number of working shifts per day, n_s
- Effective working hours per shift, t_e
- Discount factor, s (%)
- Electricity price for 1 kwh, c_e (\$/kWh)
- Total average payments per man, p_b (\$/months)

Block II. This block calculates specific transportation costs for different transportation systems:

$$c = \frac{A + T_{io} + T_e + T_{to} + T_m + T_r}{Q_g} \quad \$/t, \qquad (1)$$

Where:

A - annual depreciation costs

T_{io} - investment assurance costs

T_e - energy costs

T_{to} - equipment maintenance costs

T_m - spare parts costs

T_r - manpower costs

Schematic view of a model for calculation of technico - economic parameters of a transportation system is shown on fig. 3.

Algoritam podmodela sa prethodne slike se sastoji od tri bloka, a to su:

- blok inputa (ulaza),
- blok tehničko-ekonomske analize transportnih sistema,
- blok za izbor optimalnog transportnog sistema.

U daljem tekstu je dat detaljni opis ovih blokova.

Blok I. Unose se zajednički ulazni podaci za transportne sisteme, i to:

- godišnja proizvodnja rude koja se transportuje, Q_g (t),
- dužina transporta, L(m),
- prosečan nagib transportne prostorije, α (°); p(´),
- koef. neravnomernosti proizvodnje, k_1,
- zapreminska masa rude u rastresitom stanju, γ_r (t/m^3),
- vek eksploatacije transportnog sistema, T (godini),
- broj radnih dana u godini, z,
- broj radnih smena u danu, n_s,
- efektivno vreme rada u smeni, t_e,
- kamatna stopa kredita, s(%),
- cena 1kWh električne energije, c_e (\$/kWh) i
- prosečna bruto plata radnika, p_b (\$/mesec).

Blok II. U ovom bloku se vrši proračun različitih transportnih sistema preko određivanja njihovih minimalnih specifičnih transportnih troškova:

$$c = \frac{A + T_{io} + T_e + T_{to} + T_m + T_r}{Q_g} \quad \$/t, \qquad (1)$$

gde je:

A - vrednost godišnjeg iznosa amortizacije,

T_{io} – troškovi investicionog održavanja i osiguranje,

T_e – troškovi potrošene električne energije,

T_{to} - troškovi tekućeg održavanja,

T_m - troškovi repromaterijala i

T_r – troškovi radne snage.

Svi troškovi se izražavaju u dolarima godišnje. Šema modela za proračun tehničko-ekonomskih parametara transportnih sistema data je na slici 3.

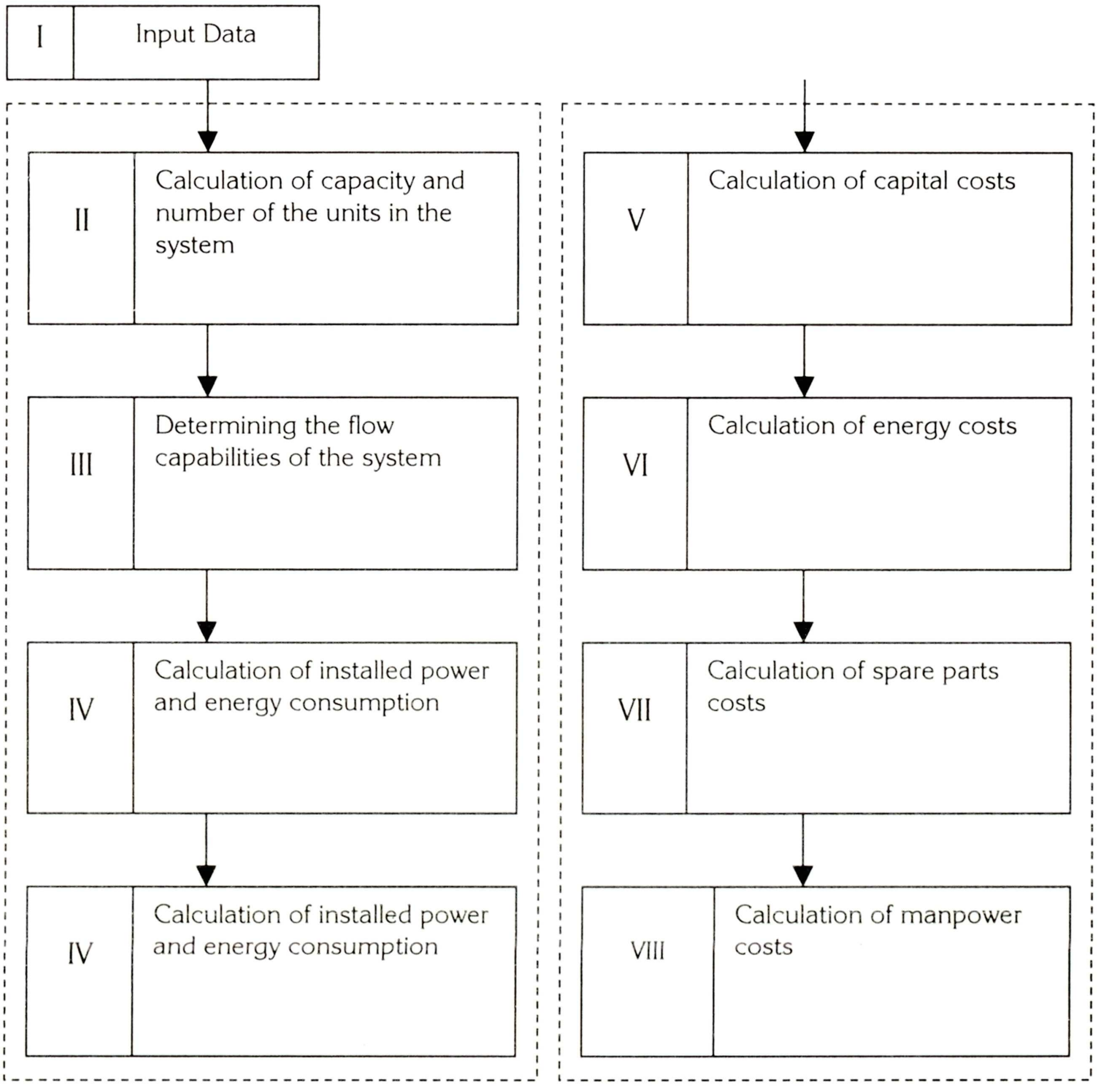

Figure 3 Calculation model for technico-ecomomic parameters of transportation systems
slika 3 Model proračuna tehničko-ekonomskih parametara transportnih sistema

Block 3. In this block specific transportation costs for different transportation systems are compared. The transportation system, which has lowest specific costs, is taken as optimal solution.

Based on the sub model for technico – economic analysis a computer program was developed.

By comparing of specific transportation costs in underground metal mines a chart for determination of optimal transportation length between rail and conveyor belt systems was developed. The capacities between 500.000 tpy and transportation length between 500 and 4.000 m' was included (see fig. 4).

Blok III. U ovom bloku se vrši upoređivanje specifičnih transportnih troškova transportnih sistema. Onaj transportni sistem sa najmanjim specifičnim transportnim troškovima je optimalno rešenje za konkretne uslove.

Na osnovu podmodela za tehničko-ekonomsku analizu izrađuje se kompjuterski program za izbor optimalnog transportnog sistema.

Upoređivanjem specifičnih transportnih troškova u uslovima rudnika sa podzemnom eksploatacijom metaličnih mineralnih sirovina došli smo do dijagrama za određivanje granične dužine upotrebe između lokomotivskog i trakastog transportnog sistema, za godišnji transportni kapacitet od 500.000 do 1.000.000 tona rude i transportno rastojanje od 500 do 4.000 m, koji je dat na slici 4.

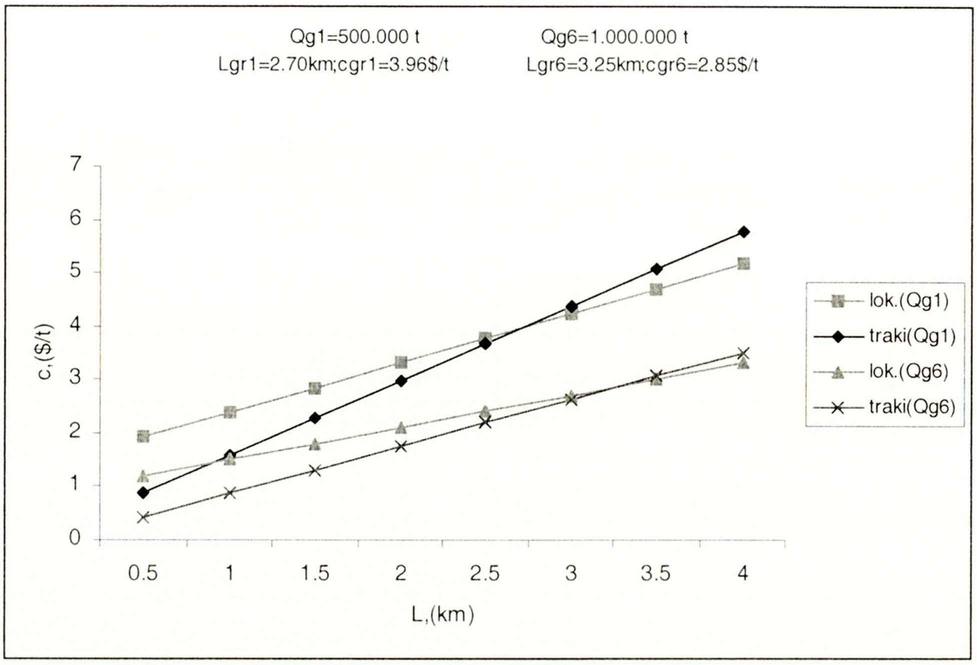

Figure 4 Chart for determination of optimal transportation length

slika 4 Dijagram određivanja granične dužine upotrebe transportnog sistema

2.2 Multi – criteria analysis

A multi-criteria analysis has variety of conflicted criterions for decision making and more alternatives from which most acceptable alternative is chosen. Mathematical model of this multi-criteria analysis could be defined in following manner:

$$\max[f_1(x), f_2(x), \ldots\ldots, f_n(x)] \quad n \geq 2 \qquad (2)$$
$$x \in A = \{a_1, a_2, \ldots\ldots\ldots\ldots, a_n\}$$

Where:
n - Number of decisions criterions
m - Number of alternatives
A – Union of known alternatives

For the transportation system designing in underground metal mines following criteria could be accepted as meaningful:

- Specific transportation costs
- Capital investment costs,
- Manpower requirements,
- System safety,
- Underground atmosphere pollution,
- System reliability and a
- Automation possibilities of the system.

Two multi-criteria decision methods are used:

- Simple Additive Weights
- PROMETHEE

2.2 Višekriterijumska analiza

Karakteristika višekriterijumskog modela je uvođenje više međusobno konfliktnih kriterijuma za odlučivanje i više alternativa za izbor, a bira se najprihvatljivija od njih. Matematički model višekritrijumskog odlučivanja može da se predstavi na sledeći način:

$$\max[f_1(x), f_2(x), \ldots\ldots, f_n(x)] \quad n \geq 2 \; ; \qquad (2)$$
$$x \in A = \{a_1, a_2, \ldots\ldots\ldots\ldots, a_n\} \, ,$$

gde su:
n - broj kriteriuma odlučuvanja,
m - broj alternativa za izbor i
A - skup raspoloživih alternativa.

Za projektovanje transportnog sistema u rudnicima za metalične mineralne sirovine u podzemnoj eksploataciji mogu da se prihvate sledeći značajni kriterijumi:

- specifični transportni troškovi,
- veličina ukupnih investicija,
- struktura radne snage,
- bezbednost rada sistema,
- pouzdanost sistema,
- zagađivanje jamskog vazduha i
- mogućnost automatizacije sistema.

U radu su razrađene dve metode iz oblasti višekriterijumske analize, i to:

- metod jednostavnih aditivnih težina i
- PROMETHEE metoda.

In the simple additive weights (SAW) method the advantage of specific criteria is expressed through the different values of weight coefficients associated by decision maker. In real problem solution with this method, processes of quantification, normalization and liberalization of attributes should do first modification of initial decision matrices. The vector of weight coefficients associated with specific criteria is:

$$T = [t_1, t_2, \ldots\ldots\ldots\ldots, t_n]. \qquad (3)$$

And following condition must be satisfied,

$$\sum_{j=1}^{n} t_j = 1 \qquad (4)$$

This method need matrices multiply:

$$OxT^T = R \qquad (5)$$

Or

$$\begin{bmatrix} l_{11} l_{12} \ldots\ldots\ldots\ldots l_{1n} \\ l_{21} l_{22} \ldots\ldots\ldots\ldots l_{2n} \\ l_{31} l_{32} \ldots\ldots\ldots\ldots l_{3n} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ l_{m1} l_{m2} \ldots\ldots\ldots\ldots l_{mn} \end{bmatrix} \times \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ \ldots \\ \ldots \\ t_n \end{bmatrix} = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ \ldots \\ \ldots \\ r_m \end{bmatrix}$$

Where $O = \|l_{ij}\|$ is linear decision matrice. Optimal solution for transportation or most acceptable alternative a* is an element of the vector R which has largest value.

The PROMETHEE method is multi-criteria decision method where alternatives ranking process is based on more decision criteria. This is iterative method consist of following steps:

- Preference structure widening and general criterion introduction
- Higher rank graph construction
- Use of higher rank relations in decision making process

The first step is to define a function of preference (P) for each two alternatives, with following possibilities:

$P(a,b) = 0$, no preference

$P(a,b) \approx 0$, weak preference

$P(a,b) \approx 1$, strong preference

$P(a,b) = 1$, hard preference

Metoda jednostavnih aditivnih težina (EAT) je karakteristična po tome što donosilac odluke, kriterijumima dodeljuje različite vrednosti težinskih koeficijenata. Pri rešavanju konkretnog problema primenom ove metode, prvo se modificira početna matrica odlučivanja postupkom kvantifikacije, normalizacije i linearizacije atributa. Vektor težinskih koeficijenata koji se dodeljuje pojedinim kritrijumima je:

$$T = [t_1, t_2, \ldots\ldots\ldots\ldots, t_n]., \qquad (3)$$

pri čemu treba da bude zadovoljen uslov:

$$\sum_{j=1}^{n} t_j = 1 \qquad (4)$$

Kod ove metode potrebno je da se formira proizvod matrica:

$$OxT^T = R, \qquad (5)$$

ili

$$\begin{bmatrix} l_{11} l_{12} \ldots\ldots\ldots\ldots l_{1n} \\ l_{21} l_{22} \ldots\ldots\ldots\ldots l_{2n} \\ l_{31} l_{32} \ldots\ldots\ldots\ldots l_{3n} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ l_{m1} l_{m2} \ldots\ldots\ldots\ldots l_{mn} \end{bmatrix} \times \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ \ldots \\ \ldots \\ t_n \end{bmatrix} = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ \ldots \\ \ldots \\ r_m \end{bmatrix}$$

gde je $O = \|l_{ij}\|$ linearizirana matrica odlučivanja. Optimalno rečenje transporta ili najprihvatljivija alternativa a^* je onaj elemenat vektora r koji ima največu brojnu vrednost.

Metoda PROMETHEE pripada grupi metoda iz oblasti višekriterijumske analize, gde se vrši rangiranje alternativa na osnovu više kriterijuma za odlučivanje, [5]. Metoda je iterativnog tipa, a proces se odvija preko sledećih postupaka:

- proširenje strukture preferencije i uvođenje opšteg kriterijuma,
- konstruiranje grafa višeg ranga i
- primena relacija višeg ranga u toku odlučivanja.

Prvi korak se sastoji u definisanju funkcije preferencije (P) za svaki par alternativa pri čemu su moguće sledeće situacije:

$P(a,b) = 0$, nema preferencija,

$P(a,b) \approx 0$, slaba preferencija,

$P(a,b) \approx 1$, jaka preferencija i

$P(a,b) = 1$, stroga preferencija.

The function of preference can be expressed as a function of x variable:

$$x = k(a) - k(b)$$

$$P(x) = \begin{Bmatrix} P(a,b), x \geq 0 \\ P(b,a), x \leq 0 \end{Bmatrix} \quad (6)$$

When real problems concerning the ore transportation are solved, only 6 general criteria are used. All these criteria are determined with preference function and their parameters, like are: simple, queasy, linear, graded, linear with indifference area and Gausian criterion.

The second step is to determine the index of preference (IP) for each two alternatives:

$$IP(a,b) = \sum_{j=1}^{n} t_j \cdot P_j(a,b) \quad (7)$$

Where:

n is a number of decision-making criteria

The third step is to determine positive and negative flow:

$$T^{+}(a) = \frac{1}{m-1} \cdot \sum_{x \in A} IP(a,x) \quad (8)$$

$$T^{-}(a) = \frac{1}{m-1} \cdot \sum_{x \in A} IP(x,a) \quad (9)$$

From the equations above a total flow (flow balance) is determined:

$$T(a) = T^{+}(a) - T^{-}(a) \quad (10)$$

This can be simply used for alternative ranking and according the PROMETHEE method following relations is possible:

aPb if and only if $T(a) > T(b)$, and

aIb if and only if $T(a) = T(b)$.

Optimal transportation solution or most acceptable alternative a* is the one which have higher value of total flow *T(a)*.

Funkcija preferencije može da se izrazi i kao funkcija promenljive x, odnosno:

$$x = k(a) - k(b)$$

$$P(x) = \begin{Bmatrix} P(a,b), x \geq 0 \\ P(b,a), x \leq 0 \end{Bmatrix}. \quad (6)$$

Pri rešavanju praktičnih problema koji se odnose na transport mineralnih sirovina najčešće se koriste 6 tipaova opštih kriterijuma koji su definisani preko funkcije preferencije, u koje spadaju: obični, kvazi, linearni, stepenasti, linearni sa područjem indeferentnosti i Gausov kriterijum.

U sledećem koraku se određuje indeks preferencije (IP) za svaki par alternativa:

$$IP(a,b) = \sum_{j=1}^{n} t_j \cdot P_j(a,b), \quad (7)$$

gde je:

n - broj kriterijuma za odlučivanje.

Treći korak se sastoji u određivanju pozitivnog i negativnog toka:

$$T^{+}(a) = \frac{1}{m-1} \cdot \sum_{x \in A} IP(a,x) \quad (8)$$

$$T^{-}(a) = \frac{1}{m-1} \cdot \sum_{x \in A} IP(x,a) \quad (9)$$

Odavde se određuje čist tok (balans toka):

$$T(a) = T^{+}(a) - T^{-}(a). \quad (10)$$

Na osnovu čistog toka vrši se rangiranje alternativa, pri čemu su moguće sledeće relacije:

aPb, ako i samo ako je: $T(a) > T(b)$ i

aIb, ako i samo ako je: $T(a) = T(b)$.

Optimalno rešenje transporta, odnosno najprihvatljivija alternativa a^* je ona koja ima najveću vrednost toka $T(a)$.

3 APPLICATION OF MATHEMATICAL MODEL FOR SELECTION OF TRANSPIRATION SYSTEM IN XIV-B DRIFT – SASA MINE

XIV-B Drift will be a main transportation route for total ore production in "Svinja River" part of the SASA mine.

Basic elements for transportation system designing in this case will be:

- Transportation length
- Annual ore production
- Transportation route inclination
- Bulk ore mass

3.1 Transportation system selection based on minimal specific transportation costs

Selection of transportation system on the base on minimal specific transportation costs was done with assistance of computer program specially developed according the technico-economic model. Rail and belt conveyer system are analyzed. We analyze 10 different alternatives for rail transportation system with variations of locomotive mass form 6 up to 15 tons and rail cars volume from 1.4 up to 4 m^3. Also 10 different alternatives for belt conveyer system was analyzed with variations of belt width from 800 up to 1200 mm and braking strength from 1000 up to 3100 kN/m. With specific transportation costs comparing an optimal alternative was selected:

Belt conveyer system with following parameters:

- Number of transporters: K=2
- Transporters length: L_{T1}=1800 m'and L_{T2}=140 m'(external conveyance)
- Belt type: EP1000/4
- Belt speed: v=2,12 m/s
- Capacity: Q_1=671 t/h
- Installed power: N_{T1}=119 kW and N_{T2}=16 kW
- Personnel needed: N_r= 6
- Total capital costs: I_V=2.844.589 $
- Specific transportations costs: c=1,59 $/t

Hanging belt conveyer system was selected for ore conveyance and trucks will be used for personnel and service transpiration.

3.2 Multi – criteria analysis for transportation system selection

Following technically possible alternatives was analyzed with multi-criteria analysis:

3 PRIMENA MATEMATIČKOG MODELA ZA IZBOR TRANSPORTNOG SISTEMA U POTKOPU XIVB

Potkop XIVB je glavni izvozni potkop u reviru Svinja Reka, rudnika za olovo i cink SASA.

Osnovni elementi za projektovanje transportnog sistema u potkopu XIVB su:

- dužina transporta: L = 1800 m,
- godišnji proizvodni kapacitet: A= 750 000 t,
- nagib transportne trase: p=3‰ i
- volumenska masa rude u rastresitom stanju γ_r =1.86 t/m^3.

3.1 Izbor transportnog sistema pomoću kriterijuma minimalnih specifičnih troškova

Pomoću kompjuterskog programa koji je baziran na tehničko-ekonomskom podmodelu izvršen je izbor transportnog sistema saglasno kriterijumu za minimalne specifične troškove. Analizirani su lokomotivski i trakasti transportni sistem i to 10 varijanti lokomotivskog transporta sa varijacijom mase lokomotiva od 6 do 15 t i volumenom vagona od 1.5 do 4m^3, a kod trakastog transporta uzeto je u obzir 10 varijanti sa različitim širinama trake od 800 do 1200 mm i čvrstinom kidanja od 1000 do 3150kN/m. Upoređivanjem specifičnih transportnih troškova transportnih sistema dobija se optimalna varijanta transporta:

Trakasti transportni sistem sa sledećim karakteristikama je:

- broj transportera: K=2,
- dužina transportera: L_{T1}=1800m i L_{T2}=140m (spoljni transport),
- tip trake: EP1000/4,
- brzina kretanja: v=2.12m/s,
- transportni kapacitet: Q_1=671t/h,
- potrebna snaga pogona: N_{T1}=119kW i N_{T2}=16kW,
- potreban broj radnika: N_r = 16,
- ukupno investiciono ulaganje: I_v=2 844 589 $ i
- spec. transportni troškovi: c=1.59$/t.

Usvojen je viseći trakasti transporter za transport rude, a za dopremanje repromaterijala i prevoz radnika predviđen je kamionski transport.

3.2 Izbor transportnog sistema pomoću metode višekriterijumske analize

Za višekriterijumsku analizu uzete su u obzir sledeće moguće alternative:

a_1:Rail transportation system with trolley locomotives
a_2: Rail transportation system with battery locomotives
a_3: Belt conveyer system with two transporters
a_4: Belt conveyer system with three transporters

Decision making criteria used for transportation system selection in XIV-B drift was like follow:

K_1 - Specific transportation costs, $/t, (min)
K_2 - Capital investment costs, mil.$, (min)
K_3 - Manpower requirements,(min)
K_4 - System safety,(max)
K_5 - Underground atmosphere pollution,(min)
K_6 - System reliability max), and
K_7 - Automation possibilities of the system (max).

a) Selection of transportation system with simple additive weights method

Multi criteria decision making matrices after quantification of qualitative attributes in following criteria, K_4, K_5, K_6 and Z are given in Table 4 and linearized decision matrice is given in Table 2.

a_1: lokomotivski transportni sistem sa trolej lokomotivama,
a_2: lokomotivski transportni sistem sa akumulatorskim lokomotivama,
a_3: trakasti transportni sistem sa dva transportera i
a_4: trakasti transportni sistem sa tri transportera.

Kriterijumi za odlučivanje pri izboru transportnog sistema u potkopu XIVB bili su sledeći:

K_1 - spec.transportni troškovi, $/t, (min),
K_2 - veličina ukupnih investicija, mil.$, (min),
K_3 - struktura radne snage, radnici, (min),
K_4 - bezbednost pri radu sistema, (max),
K_5 - zagađivanje jamskog vazduha, (min),
K_6 - pouzdanost sistema, (max) i
K_7 - mogućnost automatizacije sistema, (max).

a) Izbor transportnog sistema pomoću metode jednostavnih aditivnih težina

Matrica višekriteriumskog odlučivanja po kvantifikaciji kvalitativnih atributa u kriteriumima: K_4,K_5,K_6 i K_7 je data u tabeli 1, a linearizirana matrica odlučivanja u tabeli 2.

Table 1
Tabela 1

	K_1	K_2	K_3	K_4	K_5	K_6	K_7
min/max	min	min	min	max	min	max	max
a_1	1.73	2.137	36	3	7	5	5
a_2	1.70	1.937	46	5	7	5	3
a_3	1.59	2.846	16	9	3	9	9
a_4	1.63	2.853	19	7	5	7	7

Table 2
Tabela 2

	K_1	K_2	K_3	K_4	K_5	K_6	K_7
min/max	min	min	min	max	min	max	max
a_1	0.9191	0.9062	0.4444	0.3333	0.4286	0.5555	0.5555
a_2	0.9353	1.0	0.3478	0.5555	0.4286	0.5555	0.3333
a_3	1.0	0.6809	1.0	1.0	1.0	1.0	1.0
a_4	0.9755	0.6789	0.8421	0.7778	0.6000	0.7778	0.7778

The valves for weight coefficient vector was accepted like follow:

$$T = [0.35 \quad 0.10 \quad 0.13 \quad 0.12 \quad 0.10 \quad 0.10 \quad 0.10]$$

By multiplying of weight coefficient vector and linearized decision matrice, a vector R is obtained:

$$R = \begin{bmatrix} 0.66 \\ 0.67 \\ 0.97 \\ 0.82 \end{bmatrix}$$

Vektor težinskih koeficienata ima sledeće vrednosti:

$$T = [0.35 \quad 0.10 \quad 0.13 \quad 0.12 \quad 0.10 \quad 0.10 \quad 0.10]$$

Množenjem vektora težinskih koeficienata i linearizirane matrice odlučivanja dobija se vektor R:

$$R = \begin{bmatrix} 0.66 \\ 0.67 \\ 0.97 \\ 0.82 \end{bmatrix}$$

The number 3 element has the highest value in the R vector and so the most acceptable alternative according to the simple weight method was $a^*=a_3$, belt conveyer system with two transporters. Total alternatives ranking was a_3, a_4, a_2 and a_1, because $r_3 > r_4 > r_2 > r_1$.

Najveću vrednost u vektoru R ima treći element $r_3 = 0.97$, odnosno najprihvatljivija alternativa prema metodi jednostavnih aditivnih težina $a^* = a_3$, odnosno trakasti transportni sistem sa dva transportera. Kompletan raspored alternativa je: a_3, a_4, a_2 i a_1, jer je: $r_3 > r_4 > r_2 > r_1$.

b) Selection of transportation system with PROMETHEE method

b) Izbor transportnog sistema metodom PROMETHEE

Evaluation table with alternatives arranged according the criteria for transportation system is given in the Table 3.

Evaluciona tabela u kojoj su prikazane alternative i kriterijumi za višekriterijumski izbor transportng sistema data je u tabeli 3.

A value of index of preference for each alternative and input – output flows and total flow was given in Table 4.

Iindeksi preferencije za svaku alternativu, kao i vrednosti ulazno-izlaznih tokova i čisti tok su dati u tabeli 4.

Final ranking of alternatives based on the total flow values is given in Table 5.

Na osnovu veličine čistih tokova (tabela 5) može da se izvrši potpuno rangiranje alternativa.

Table 3
Tabela 3

	K_1	K_2	K_3	K_4	K_5	K_6	K_7
min/max	min	min	min	max	min	max	max
a_1	1.73	2.137	36	3	7	5	5
a_2	1.70	1.937	46	5	7	5	3
a_3	1.59	2.846	16	9	3	9	9
a_4	1.63	2.853	19	7	5	7	7
general criterion.	linear (III)	linear (III)	graded (IV)	graded (IV)	linear(III)	linear(III)	linear (III)
param. m				2	2		
n	0.14	0.92	30	4	4	4	6
weights	0.35	0.10	0.13	0.12	0.10	0.10	0.10

Table 4
Tabela 4

	a_1	a_2	a_3	a_4	T^+	T
a_1	0	0.0666	0.077	0.0778	0.074	-0.368
a_2	0.0966	0	0.0983	0.0996	0.098	-0.289
a_3	0.7734	0.7001	0	0.1944	0.556	**0.497**
a_4	0.4549	0.3817	0	0	0.279	0.155
T^-	0.442	0.383	0.059	0.124		

Table 5
Tabela 5

	T	rank
a_3	0.497	1
a_4	0.155	2
a_2	-0.285	3
a_1	-0.368	4

The most acceptable alternative based on the date above was $a^*=a_3$ because it has largest total flow value.

From here we can see that according the PROMETHEE method the belt conveyer system with two transporters was also selected as most acceptable transportation system.

U tabeli 5. može da se vidi da je najprihvatljivija alternativa $a^* = a_3$, jer ima najveću vrednost čistog toka.

Znači, i primenom metode PROMETHEE najprihvatljivija alternativa transportnog sistema u potkopu XIVB je: trakasti transportni sistem sa dva transportera, čije karakteristike su navedene u tački 3.1 u ovom radu.

4 CONCLUSION

The mathematical model proposed offers a complete analyzing toll for transportation system selection in underground metal mining through the following approaches; multi criteria and single criterion.

The single criterion was not providing a real picture for the problem solved and the attention was directed to economic aspects only, while other criteria (safety, reliability, automation...) was depleted. Multi – criteria approach gives us opportunity for really optimal solution of transportation problems, with unavoidable incorporation o single criterion analysis lake starting point.

4 ZAKLJUČAK

Predloženi matematički model omogućava kompletnu analizu pri projektovanju podzemnih transportnih sistema, preko dva pristupa: jednokriterijumskog i višekriterijumskog.

Jednokriterijumski pristup ne daje realnu sliku za dati problem jer je težište problema u ekonomskom delu (spec. transportni troškovi), a pritom zapostavlja ostale kriterijume (bezbednost, pouzdanost, automatizaciju i dr.). Višekriterijumski pristup omogućava realnije i egzaktnije rešavanje transportnih sistema, no sa neizbežnim uključivanjem jednokriterijumskog pristupa kao polaznom osnovom.

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