Truck Selection with the Fuzzy-WSM Method in Transportation Systems of Open Pit Mines

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Abstract: Open pit mines gain width and become more complicated as they are deeper today, and it is inevitable to carry the produced material with a truck transportation system. Therefore, in large-scale businesses, truck selection has great importance for the transportation costs to be sustainable. This study investigates the main factors and corresponding criteria influential in selection of trucks, which are the most frequent used means of transportation in open pit mines. Analytic hierarchy process and fuzzy weighted sum model are employed to solve the selection problem. Six different truck types and 20 selection criteria are considered. As a result of technical analysis, most suitable trucks are found.

Keywords: Fuzzy Weighted-Sum Model (FWSM); mining truck; open pit mine; truck transportation

1 INTRODUCTION

Open pit mines get deeper and gain width as resources are consumed on the surface. In open pit mines, nearly one third of the unit cost comes from haulage operation. Since haulage makes up a substantial part of unit cost, these operations should be considered carefully and analysed in detail especially for technical and work safety factors. Improvement and upgrade work to be conducted in the transportation system, and reduction of transportation operation costs which are thought to be close to half of the operation costs by a few percentage points, will provide significant gains for the economy of the operation. Developments in the world's mining industry and increases in production are made possible by the usage of high capacity transportation vehicles. The aim to reduce unit costs necessitated the introduction of higher capacity, faster and technologically more advanced, well-equipped machinery and equipment.

Selection of machinery-equipment in mining is one of the most important parameters influential on the unit production cost. Parameters such as technical usability, economic goals, performance and workplace safety should be included in this assessment. Increased capacity of the machinery-equipment decreases its abilities in movement. On the other hand, with lower capacity, capability of movement increases, but the unit costs increase. Therefore, technical and economic parameters should be considered together for the pit where the operation will be run [1]. In the machinery-equipment selection stage, precise data must be used in compliance with mathematics and engineering application principles to find the economic solution [2, 3].

Selecting the most suitable equipment for transportation becomes an important factor that affects the cost [1]. Process of transportation consists of dynamic variables such as condition and grade of the roads, performance of the trucks etc. Condition of the road implies constantly changing parameters such as transportation distance, maximum allowed speed, stability and rolling resistance of the road. Each of these parameters influences transportation cycle-time for a truck (loaded and unloaded trips) and indirectly causes effects on the consumption of fuel, oil, hydraulics and furthermore on the economical life of equipment being used [4].

Transportation costs make up nearly half of operation costs [5]. Therefore decreasing transportation costs by a few points would save the mine considerable amount of money. Haulage can be made vertically, horizontally or in an inclined direction. In open operations, the transportation system is generally dependent on working conditions, reserve amounts, thickness and characteristics of top layer, annual production capacity, and layer-digging volume. Optimum machinery-equipment is selected for its suitability for the operating conditions and capacity. In many of the cases, two or more transportation modes can be employed together. When different haulage systems are considered, it can be seen that truck haulage has the smallest initial investment cost [6].

In addition, the most important factor in choosing truck transportation is that it has advantages of easy adaptation to rough land conditions in cover material and coal transportation when the mine is deeper, and its relatively lower fixed cost in the beginning, which provides economic advantages. The roughness of the land and the factor of slope of the coal make displacement among panels harder, but increase the applicability of truck transportation systems. Moreover, in cases of continuous transportation operations, any error or problem in the system may interrupt the continuity of the operation. The most important advantage is that the continuity of the transportation may be sustained even if one or more trucks are faulty in the line. Another benefit brought by this advantage is that trucks are able to work in different environments in the pit [5, 6]. Considering all these advantages, it is inevitable to carry the produced material with a truck transportation system. Therefore, truck selection has great importance for the transportation costs to be sustainable.

However, while truck transportation systems are the most frequently preferred systems in open pit mining, their operating costs are higher in comparison to other systems of transportation. Therefore selecting the most suitable truck alternative becomes an important problem to decrease operation costs. In this study, the aim is to investigate the main factors and related criteria influential in selection of trucks. Then, alternative truck types are analysed based on the decision criteria and ranked according to overall performance.

Cost-effectiveness in mining requires working with high-capacity machinery. This makes the initial investment

costs high. Many factors are effective in machine selection problems in mining. In such complicated problems, the selection can be made more reliably by using multi-criteria decision making (MCDM) tools.

In the study, truck selection problem in open pit mining is considered by MCDM. The tools used are analytic hierarchy process (AHP) and fuzzy weighted sum model (FWSM) respectively. AHP is employed to determine the influences of selection criteria on the decision and FWSM is employed to rank the decision alternatives (mine trucks). The proposed methodology integrates these two tools in an effective way. Also, by incorporating fuzzy logic into the truck selection problem, error, bias and subjectivity are decreased in the decision process.

2 SELECTION PROBLEM

Diversity of transportation in open pit mining may vary based on the developments in pit production aspects and increases in the depth of the site. Therefore, transportation selection problems, transportation vehicle capacity and cycle problems in mines are problems that are widely studied in the literature. Bascetin & Kesimal [7], Naoum & Haidar [8], Marzouk & Moselhi [9], Wei et al. [10], Bitarafan & Ataei [11], Samanta et al. [12] considered equipment selection at open pit mines, Yavuz [13] selected the production method of an underground mine, Ozkan et al. [14] evaluated resource classification, Ataei [15] handled facility location selection, Bottero & Peila [16] compared two different excavation techniques, Yaria et al. [17] used TOPSIS method in addition to AHP and Kumar & Kaur [18] considered fuzzy solid transportation problem for supplying coal in their studies.

Figure 1 Open pit mine and truck transportation [20]

Truck selection problem is frequently encountered in open pit operations. However, truck selection may become a complicated problem based on annual stripping amounts and reserve amounts. While Kose et al. [4] mentioned the advantages of truck transportation in open pits, they emphasized that technical factors such as production type on the top layer, changes in loading areas, changes in transportation speed, and the physical and chemical characteristics of the loaded material must be investigated carefully. Also, it is stated in literature that inconvenient roads, inappropriate dumping and vibrations decrease the economic life of equipments [5, 6].

More recently, autonomous trucks are getting into use for both underground and surface mining. These trucks increase safety and decrease labour at the same time [19].

High-capacity trucks draw attention with their superiority over low-capacity trucks in terms of their hourly capacity and efficiency. The economy created by their advantages should also not be ignored. Thus, it is aimed to describe the specific characteristics and usage criteria of these trucks, and they need to be compared to other trucks in terms of technical and economic aspects. Truck transportation is showed in Fig. 1 [20].

3 METHODOLOGY

In the solution methodology, analytic hierarchy process (AHP) and fuzzy weighted sum model (F-WSM) is employed. In the first phase, AHP is used to determine the weight coefficients of decision criteria. Then these coefficients are turned into fuzzy triangular numbers and F-WSM is applied to determine the superior alternatives. The solution approach is explained in detail in the following.

3.1 Determine Selection Criteria and Apply AHP to Compute Priorities

The first step is to determine the decision criteria. Once these criteria are settled, AHP is employed to compute the priorities of each criterion. In addition to priority coefficients of decision criteria, inconsistency ratio is also computed. Let the inconsistency ratio be RI inconsistency ratio is especially important for the proposed methodology because it will be used to transform crisp numbers to fuzzy numbers in step 2. Therefore, if value of RI is greater than 0.1, pairwise comparison matrices should be revised and priorities should be re-computed. If value of RI is less than 0.1, the procedure goes on with the next step.

3.2 Develop Fuzzy Priorities

The crisp priorities obtained by AHP in the first step are transformed into fuzzy triangular numbers in this step. Let p_i be the priority coefficient computed for criterion i. Then, the priority matrix obtained by AHP for the n decision criteria would be as in Eq. (1).

$$P = \left[p_1, p_2, p_3, \ldots, p_n \right] \tag{1}$$

In order to transform crisp priorities into fuzzy triangular numbers, a lower bound and an upper bound should be computed. Let the fuzzy triangular number to represent crisp priority p_i be:

$$\left[lp_i, \ p_i, \ up_i \right] \tag{2}$$

where:

lp_i: lower bound for priority p_i,
up_i: upper bound for priority p_i.

Then lp_i and up_i are computed as in Eqs. (3) and (4) respectively.

$$lp_i = (1 - RI) \times p_i \qquad (3)$$

$$up_i = (1 + RI) \times p_i \qquad (4)$$

These bounds are found based on the idea that since there exists RI amount of inconsistency in AHP calculations, the consistent values of the corresponding priorities can be found by adding and subtracting this RI amount from the value of the priority.

3.3 Develop Fuzzy Priorities

Once the decision criteria and fuzzy triangular priorities are settled, alternative decision options should be identified. Let there be k alternative options. Fuzzy performance matrices for all k alternatives according to all decision criteria should be developed (Eq. 5). In other words, the performance of each alternative should be represented by a fuzzy triangular number. In order to do so, the worst case, most likely and the best case performance scores should be determined for all k alternatives.

$$Performance = \begin{bmatrix} w_1 & m_1 & b_1 \\ \dots & \dots & \dots \\ w_k & m_k & b_k \end{bmatrix} \qquad (5)$$

where:

w_i: worst case performance score for alternative i,
m_i: most likely performance score for alternative i,
b_i: best case performance score for alternative i.

3.4 Compute Overall Performance Using Fuzzy-Weighted Sum Model

In this step, fuzzy weighted sum model is employed to find the overall fuzzy performances of each alternative (Eq. (6)).

$$P_i = \left[\sum w_i \cdot p_i, \quad \sum m_i \cdot p_i, \quad \sum b_i \cdot up_i \right] \forall i = 1, \dots, k \qquad (6)$$

Eq. (6) outputs fuzzy triangular numbers representing the performance of alternative trucks. The corresponding membership functions for the fuzzy triangular numbers are given as in Eq. (7).

$$\mu_i(x) = \begin{cases} 0 \text{ if } x \leq \sum w_i \cdot lp_i \text{ or } \sum b_i \cdot up_i < x \\ \dfrac{x - \sum w_i \cdot lp_i}{\sum m_i \cdot p_i - \sum w_i \cdot lp_i} \text{ if } \sum w_i \cdot lp_i < x \leq \sum m_i \cdot p_i \\ \dfrac{\sum b_i \cdot up_i - x}{\sum b_i \cdot up_i - \sum m_i \cdot p_i} \text{ if } \sum m_i \cdot p_i < x \leq \sum b_i \cdot up_i \end{cases} \qquad (7)$$

3.5 Comparison and Ranking of Fuzzy Performances

When two fuzzy triangular numbers (Overall Performance i and Overall Performance j) are with membership functions $\mu i(x)$ and $\mu j(y)$ compared, Overall Performance i dominates Overall Performance j if the following conditions (Eq. (8)) are satisfied [21]:

$$d_{ij} = 1 \text{ and } d_{ji} < \text{Threshold} \qquad (8)$$

where d_{ij} is computed as in Eq. (9) and Threshold can be determined to be 0.7, 0.8 or 0.9 by the decision makers of the system [21].

$$d_{ij} = \max_{x \geq y} \left\{ \min(\mu_i(x), \mu_j(y)) \right\} \qquad (9)$$

In this study, Threshold is determined to be 0.9 and the methodology is applied to rank the overall performances of mine trucks.

4 APPLICATION OF THE MODEL METHODOLOGY

The model implementation explained in the previous section of the study is applied to GLI's open pit. Tunçbilek coalfield is located 50 km far from Kutahya province and 13 km far from the district of Tavsanli. Significant portion of the lignite reserves in Turkey is located in Tuncbilek (252.5 million tons). About 7% of the country's lignite production is provided by this area. The produced coal is fed from here to the thermal power plant with the installed power of 365 MW [20]. Tab. 1 shows the important parameters of production for the operation.

Table 1 The Operation's Technical Values [20]

Production parameters	Values
Coal calorific value	2560 kcal/kg
Annual coal production (from open pit)	4.5 million ton
Annual stripping (from TKI)	10 million m^3
Stripping ratio	13 m^3/t
Total reserve amount	252.5 million tons
Installed Thermic plant power	365 MW

Garp Lignite Company provides approximately 87% of the programmed 4.5 million ton/year raw lignite coal production from the open pit. In preparation of panels for coal production in the open operation, dragline and excavator-truck layer digging is used. The average layer digging ratio is 13, and approximately 10000000 m^3 of top layer digging is made to achieve annual planned coal production [20]. Striping trucks are considered in this study. The detailed case study is given in the following.

4.1 Determine Selection Criteria and Apply AHP to Compute Priorities

The purpose of the model study is to determine the truck capacities to be selected during the transportation of 10 million m^3 of material through a year. The main purpose of the model, main criteria and Sub-criteria are given in Fig. 2 and Tab. 2.

As seen in Tab. 2, main criteria groups are Economy (C1), Technical constraints (C2), work safety (C3) and Truck properties (C4) respectively. Each of these groups are considered in detail in the following.

Economy (C1): Economy criteria are fuel consumption (C11), working time (C12), initial investment cost (C13), Depreciation (C14), Material transportation unit cost (C15)

according to the literature studies and authors of the study [22-24]. Annual average working time of mine trucks are important. Accordingly, the ratios of electrical failures and mechanical failures in the total active and stationary times of the truck are important. A low value of these ratios in total hours indicates a high efficiency for these trucks. In addition, depreciation and unit cost also are important factors. Especially, initial investment cost and operating cost quite affect truck selection problem [25]. For example, more tonnage trucks investment is more expensive but operating cost is less.
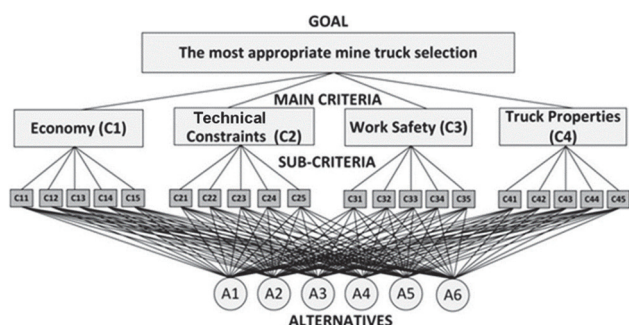

Figure 2 Decision hierarchy for the mine truck selection problem

Table 2 Main Criteria and Sub-Criteria for the Truck Selection Problem

C1: Economy	C2: Technical constraints
C11: Fuel consumption	C21: Efficiency
C12: Working time	C22: Compatibility capacity of
C13: Initial investment cost	truck and loader
C14: Depreciation	C23: Transport capacity
C15: Material transportation unit cost	C24: Slope of the transportation route
	C25: Production system
C3: Work safety	**C4: Truck properties**
C31: Technology and safety systems (Navigation, truck dispatching system etc.)	C41: Truck capacity
	C42: Engine power
	C43: Engine type
C32: Vibration and impact strength of the truck vessel	C44: Gearbox
C33: Gas emissions	C45: Equipment
C34: Cabin comfort and ergonomics	
C35: Noise	

Technical constraints (C2): Technical constraints can be grouped as efficiency (C21), compatibility capacity of truck and loader (C22), transport capacity (C23), slope of the transportation route (C24) and production system (C25). Especially Ta et al. [26] and Ankara et al. [27] emphasized that working times should be more than failure times of trucks for efficiency. Compatibility capacity of truck-loader and transport capacity are primarily important in the determination of the amount of material to be transported hourly [28]. On the other hand, pit roads must be designed with 8-12% of slope for the best efficiency of trucks. Finally, production system also affects truck selection. Two sided maneuvering system is more preferred in operations as it reduces cycle time [4].

Work safety (C3): Work safety criteria are Technology and safety systems (C31), vibration and impact strength of the truck vessel (C32), gas emissions (C33), cabin comfort and ergonomics (C34) and noise (C35). Ozfirat et al. [29] and Mutlu [30] has shown that about 30% of accidents in ELİ open pits were caused by mining machinery and equipment. Today, navigation, truck dispatching system

has been developed. Malli et al. [31] emphasized navigation, GPS-based, truck allocation-monitoring system technologies. Big mining machinery firms have developed monitoring, mining machinery allocation, defining potential hazards and alert to operators around their machines which assure safer working conditions. In addition, these systems serve mines as a comprehensive overview of all operations with real time machine tracking and productivity management. Moreover, working with comfortable, noise-reducing cabin systems with low vibration, environment-friendly engines with catalytic converter systems and Euro 5-compatible emissions, would reduce the amount of workplace accidents and increase the standards of workplace safety.

Truck properties (C4): Truck properties are also important for truck selection problem. Truck properties are determined as truck capacity (C41), engine power (C42), engine type (C43), gearbox (C44). Truck capacity is the most important for truck selection problem. For example, investment in large-capacity trucks is inevitable in deep open pit mines with an annual stripping amount of more than 5-10 million tons. As Kose et al. [4] emphasize, as the mine gets deeper, electric power type becomes more economical and more environment-friendly instead of diesel power. In addition, since mine conditions are difficult, truck manufacturers must produce machine attachments and equipment resistant to mine conditions.

Table 3 Priorities for decision criteria found by AHP

C1: Economy		C2: Technical constraints	
C11	0.094	C21	0.039
C12	0.025	C22	0.056
C13	0.054	C23	0.080
C14	0.054	C24	0.012
C15	0.182	C25	0.015
Sum	0.409	Sum	0.202
C3: Work safety		**C4: Truck properties**	
C31	0.139	C41	0.035
C32	0.064	C42	0.025
C33	0.021	C43	0.014
C34	0.040	C44	0.008
C35	0.028	C45	0.015
Sum	0.292	Sum	0.097
Overall Inconsistency Ratio = 0.097			

After determination of the decision criteria, AHP is applied to find priority coefficients of all criteria. The priorities can be seen in Tab. 3 above. Economy (C1) turned out to be the most effective criteria group in truck selection and work safety (C3) takes the second place. In addition, it is found that transportation unit cost (C15: 0.182), technology and safety systems (C31: 0.139), fuel consumption (C11: 0.094) and work capacity (C23: 0.08) are primarily important. Also, the overall inconsistency ratio is found to be 0.097. This is an acceptable level since it is less than 0.1 Threshold.

4.2 Develop Fuzzy Priorities

At this step, crisp priorities given in Tab. 3 are transformed into fuzzy priorities using the overall inconsistency ratio and applying Eqs. (3) and (4). Fuzzy priorities belonging to each decision criterion can be seen in Tab. 4.

Table 4 Fuzzy priorities for decision criteria

	Lower	Middle	Upper
C11	0.085	0.094	0.103
C12	0.022	0.025	0.027
C13	0.048	0.054	0.059
C14	0.049	0.054	0.059
C15	0.164	0.182	0.200
C21	0.035	0.039	0.043
C22	0.051	0.056	0.062
C23	0.073	0.080	0.088
C24	0.011	0.012	0.014
C25	0.013	0.015	0.016
C31	0.125	0.139	0.152
C32	0.058	0.064	0.071
C33	0.019	0.021	0.023
C34	0.036	0.040	0.044
C35	0.025	0.028	0.031
C41	0.032	0.035	0.039
C42	0.022	0.025	0.027
C43	0.012	0.014	0.015
C44	0.008	0.008	0.009
C45	0.014	0.015	0.016

4.3 Identify Alternative Options and Develop Fuzzy Performance Matrices

Nowadays, electric drive mine trucks reach up to 400 tons [32]. In the modelling studies, mine stripping trucks with six different capacities were considered. According to Burt & Caccetta [23], Burt et al. [33] and Topal & Ramazan [34], 5 to 25 different types of trucks may be used. However, considering the widespread usage in the most general sense and the conditions of the study site, alternative options given in Tab. 5 are considered [35]. As diesel trucks are used in the area, all types are considered to be diesel trucks.

Table 5 Truck options [35]

Alternatives	Capacity (ton)	Class
A1: Mine Truck 1	≤ 35 tons	Light
A2: Mine Truck 2	35 < capacity < 55 tons	Light Medium
A3: Mine Truck 3	55 < capacity < 85 tons	Medium
A4: Mine Truck 4	85 < capacity < 170 tons	Medium
A5: Mine Truck 5	170 < capacity < 270 tons	Medium-Heavy
A6: Mine Truck 6	270 < capacity tons	Heavy

After the types of trucks are determined, they are analysed based on all criteria according to fuzzy logic. Tab. 6 shows the fuzzy triangular numbers representing the performances of each alternative truck. In the analysis, types of trucks are given a score of 0 to 100 based on the criterion performance. For example, line C13 in Tab. 4 gives the performance scores based on the initial investment criterion. As initial investment costs increase with the capacity of the trucks, lowest performance belongs to A6 (which has the highest capacity). In addition, the fuzzy performance for this truck is determined to be (55, 65, 75) which shows the worst case, most likely and best case performance scores respectively.

Table 6 Fuzzy performance scores of alternative mine trucks

Criteria	A1	A2	A3	A4	A5	A6
C11	(60, 75, 80)	(55, 65, 75)	(60, 70, 75)	(65, 75, 80)	(75, 80, 90)	(85, 95, 100)
C12	(75, 80, 85)	(70, 75, 80)	(70, 80, 85)	(65, 75, 80)	(70, 75, 80)	(65, 70, 75)
C13	(80, 90, 100)	(75, 80, 95)	(70, 80, 90)	(65, 75, 85)	(60, 70, 80)	(55, 65, 75)
C14	(65, 70, 75)	(65, 75, 80)	(65, 80, 85)	(70, 85, 90)	(85, 90, 95)	(90, 95, 100)
C15	(60, 65, 70)	(50, 55, 60)	(60, 65, 70)	(70, 75, 80)	(75, 80, 90)	(90, 95, 100)
C21	(65, 70, 75)	(65, 75, 80)	(75, 80, 85)	(70, 85, 90)	(85, 90, 95)	(90, 95, 100)
C22	(85, 90, 95)	(75, 80, 85)	(70, 75, 80)	(65, 75, 80)	(65, 70, 75)	(60, 65, 70)
C23	(60, 65, 70)	(65, 70, 75)	(70, 75, 80)	(70, 75, 85)	(75, 80, 90)	(85, 90, 95)
C24	(70, 75, 80)	(65, 75, 80)	(65, 70, 75)	(65, 70, 75)	(60, 65, 70)	(60, 65, 70)
C25	(85, 90, 95)	(80, 85, 95)	(80, 85, 95)	(80, 85, 90)	(75, 80, 90)	(75, 80, 85)
C31	(65, 70, 75)	(65, 70, 80)	(75, 80, 85)	(80, 85, 90)	(85, 90, 95)	(90, 95, 100)
C32	(65, 70, 75)	(65, 70, 75)	(70, 75, 80)	(70, 75, 80)	(70, 75, 85)	(80, 85, 90)
C33	(90, 95, 100)	(85, 90, 95)	(80, 85, 90)	(75, 80, 85)	(65, 70, 80)	(65, 70, 75)
C34	(65, 70, 75)	(65, 70, 75)	(70, 75, 80)	(70, 75, 80)	(70, 75, 85)	(80, 85, 90)
C35	(75, 80, 85)	(75, 80, 85)	(65, 75, 80)	(65, 75, 80)	(65, 70, 75)	(65, 70, 75)
C41	(70, 75, 80)	(75, 80, 85)	(80, 85, 90)	(80, 85, 90)	(85, 90, 95)	(90, 95, 100)
C42	(70, 75, 80)	(75, 80, 85)	(80, 85, 90)	(80, 85, 90)	(85, 90, 95)	(90, 95, 100)
C43	(70, 75, 80)	(75, 80, 85)	(80, 85, 90)	(80, 85, 90)	(80, 90, 95)	(85, 95, 100)
C44	(70, 75, 80)	(70, 80, 85)	(80, 85, 90)	(80, 85, 90)	(80, 85, 95)	(80, 90, 100)
C45	(70, 75, 80)	(75, 80, 85)	(80, 85, 90)	(80, 85, 90)	(85, 90, 95)	(90, 95, 100)

4.4 Compute Overall Performance Using Fuzzy-Weighted Sum Model

Overall performance for each of the six alternative mine trucks are computed using FWSM. Results can be seen in Tab. 7. In addition the membership functions belonging to each fuzzy performance are presented in Fig. 3.

Table 7 Overall fuzzy performance scores of alternative mine trucks

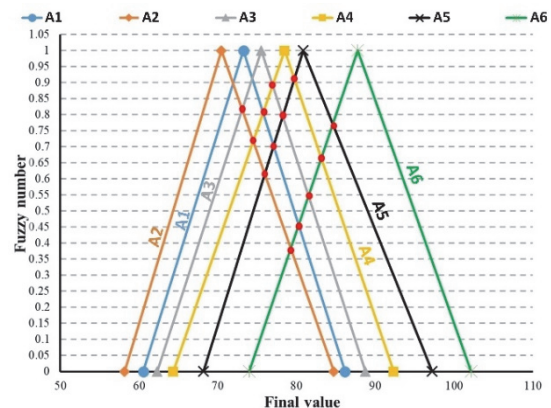| Mine Truck	Overall Performance in Fuzzy Triangular Numbers
A1	(60.54; 73.25; 86.14)
A2	(58.16; 70.44; 84.70)
A3	(62.30; 75.53; 88.71)
A4	(64.35; 78.48; 92.31)
A5	(68.16; 80.82; 97.21)
A6	(73.98; 87.77; 102.11)

Figure 3 Membership functions fuzzy performances of mine trucks

4.5 Comparison and Ranking of Fuzzy Performances

When ranking fuzzy performances of mine trucks, Threshold level is determined to be 0.9. d_{ij} values are computed according to Eq.(9) and presented in Tab. 8.

Table 8 d_{ij} values to rank overall fuzzy performances of mine trucks

i \ j	1	2	3	4	5	6
1	-	1	0.91	0.81	0.7	0.46
2	0.895	-	0.82	0.72	0.62	0.38
3	1	1	-	0.89	0.8	0.55
4	1	1	1	-	0.91	0.67
5	1	1	1	1	-	0.77
6	1	1	1	1	1	-

Considering the conditions given in Eq. (8), it can be seen from Tab. 8 that,
- Mine truck 6 dominates all other alternatives ($d_{6j} = 1$ and $d_{i6} < 0.9$ for all $i \neq 6$ and $j \neq 6$).
- Mine truck 5 dominates mine trucks 3, 1 and 2. However, we are indifferent between mine truck 5 and 4 (Since $d_{45} = 0.91 > 0.9$).
- Mine truck 4 dominates mine trucks 3, 1 and 2.
- Mine truck 3 dominates mine trucks 2. However, we are indifferent between mine truck 3 and 1 (Since $d_{13} = 0.91 > 0.9$).
- Mine truck 1 dominates mine truck 2.

5 DISCUSSIONS AND RESULTS

Developments in the world's mining industry and increases in production are made possible by the usage of high-capacity transportation vehicles. Technologically more advanced machinery-equipment has more advantages in minimization of unit cost, and maximization of work safety standards.

The effects of the main factors and the Sub-criteria in selection of trucks are investigated with the method of AHP and FWSM. It is found that among the main criteria groups, economy (C1: 0.409) and work safety (C3: 0.292) criteria have the highest influences on the decision. In addition, among the Sub-criteria, it is observed that especially the transportation unit cost is effective. Bozorgebrahimi et al. [22], Kose et al. [4], Burt & Caccetta [23], Kose & Kahraman [25] emphasized importance of economic analysis on truck selection problem. Similar to these studies, the most important selection criterion is determined to be economic analysis. However, different from these studies in the literature, this study considers truck selection problem using a fuzzy model. Also, work safety is found to be the second influencing criterion. This is an expected result since work safety rules and regulations are getting more important in today's manufacturing environment. Therefore, working with safer technologies and safer work regulations in mining have made the work safety criterion important in truck selection problem. Truck manufacturers are now trying to eliminate all the hazards that will occur in the open pit with GPS navigation, truck monitoring, truck dispatch, machine maintenance and efficiency monitoring systems.

As a result of the FWSM analysis, it is found that Mine Truck 6 (capacity > 270 tons: heavy) is determined to be the most suitable for the area under study. Mine Truck 5 (170 < capacity < 270 tons: medium-heavy) and Mine Truck 4 (85 < capacity < 170 tons: medium) are found as

equivalent to each other in the selection. Mine Truck 1 and Mine Truck 3 may be considered equivalent, and more preferable compared to Mine Truck 2. The results show that large capacity truck investments are preferred, especially in deep and large capacity mines.

6 CONCLUSION

Selection problems are the most difficult ones especially in mining studies, because machinery investments are highly costly investments. Thus, in cases where the wrong machinery or machinery with the wrong capacity is used, operations are not cost-effective and they may even come to a point of stopping. This creates serious problems for mines. Therefore, decision problems in mining must be analysed in detail by multi-criteria decision making techniques. In the study, truck selection problem in an open pit mine is handled and a solution methodology integrating AHP and FWSM is proposed. With the incorporation of fuzzy logic, the model leads to solutions prone to less error and bias. The methodology is also applied to real life case study. In the solutions, ranking of alternative truck types according to their overall performances are computed and presented.

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