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Selecting the TMF alternatives based on the multi-criteria decision analysis

DAN STEMATIU*

Technical Sciences Academy of Romania

Abstract. Multiple criteria decision analysis, or MCDA, is a structured process for evaluating options with conflicting criteria and choosing the best solution. MCDA is similar to a cost-benefit analysis but evaluates numerous criteria, rather than just cost. It allows to identifying and comparing different options by assessing their impacts, performances, advantages, and disadvantages, leading to a consistent decision-making. In order to underline the benefits of this approach the paper presents a study case selected from the mining industry. The Certej gold mining project is located within the Apuseni and Metaliferi mountains of Romania. The processing of the Certej ore deposit needs tailings management facilities (TMF). The Flotation TMF will be required to house 40.5 million tones of tailings during mining life. In the area of the project were found two possible locations with certain advantages and disadvantages. Selection of the most advantageous option based on MCDA is presented in the paper.

Keywords: multiple criteria analysis, ore mining, tailings management.

1. The principles of the multi-criteria decision analysis

Multiple criteria decision analysis, or MCDA is useful and mandatory to divide the alternatives of various classes, established on various criteria, if the assessment of the alternative effects can not be brought to a common natural measure unit.

There are various heuristic methods of multi-criteria decision, worldwide used, among which some are classical methods. Here is a simplified method, derived from the ELECTRE method, which brings the alternatives to a common conventional measure unit, called „the score". Mainly, it consists of the addition of scores granted to the alternatives, analyzed per each criterion, and weighted by the criteria significance. The alternative with the highest score is the optimum one per all the criteria.

*Correspondence address: dan.stematiu@utcb.ro

1.1. Establishing the criteria

The criteria may differ depending on the situation, and on the type of project. Usually, in order for the deciding entities to be in control of the analysis process, the selection is limited to 5-8 criteria, to which the "zero" fictive criterion is added [1]. This criterion is less important than all the others and it is automatically eliminated, thus avoiding the possible elimination of an important criterion.

1.2. Ranking and establishing the criteria percentage

The deciding entity (the analyst) compares the selected criteria - C_i (I =1,2,3....m) by pairs, (trying to disconfirm the rest of the criteria) and grants 2 points to the one considered (mainly subjectively) as the most important for the analyzed case, and records them in the adequate column (where he summed up the points); naturally, in the box, symmetrically positioned in relation to the main diagonal, the 0 number shall be recorded. In case of indecision, 1 point is granted to each criterion, and it is recorded in the two criteria intersection boxes symmetrically positioned in relation to the main diagonal.

Trying to independently compare each pair of criteria is very important; it can lead to a logically catch ($C_1 > C_2, C_2 > C_3, C_3 > C_1$), but this catch is less important than the effect of prejudices elimination, which may lead to the criteria "arranging" depending on a previous opinion [2],[3].

To mitigate the subjective character incidental to any decision maker, but, most importantly, to consider the opinion of several persons involved in the decision-making process and analysis process, such matrix may be independently replaced; the final percentages being the average of the percentages obtained by all the decision makers. The average may be an average weighted depending on the competence and/or responsibility of the decision makers, established a priori.

The results obtained by each decision maker are recorded in a matrix like the following one, filled in for exemplification.

CRITERIA		CRITERIA					
		C_1	C_2	C_3	C_4	C_5	C_6
CRITERIA	C_1		0	1	0	2	0
	C_2	2		0	0	1	0
	C_3	1	2		1	2	0
	C_4	2	2	1		2	0
	C_5	0	1	0	0		0
	C_6	2	2	2	2	2	
Total points	t_i	**7**	**7**	**4**	**3**	**9**	**0**

Each C_i criterion shall obtain a t_i score, the so-called "zero criterion" being kept: in the given example, C_6, shall have t_6=0. The total score of the criteria shall be

$T = \Sigma t_i = m^2 - m$. The percentage of a criterion shall be $p_i = t_i / T$, thus $\Sigma p_i = 1$. The result is: $p_1 = p_2 = 7/30 = 0{,}233$; $p_3 = 0{,}133$; $p_4 = 0{,}1$; $p_5 = 0{,}4$.

1.3. Establishing the alternatives

Based on the same criteria and under the same circumstances as the ones illustrated by the matrix method in the comparative analysis, n project alternatives are established V_j, with (j=1, 2, ... *n*), significantly different regarding the effects. In the case of the analysis on the decision regarding the project opportunity, one of the alternatives shall be the "zero alternative", namely, the project non-execution. Due to reasons similar to the previous ones, it is recommended that n≤6, the analysis of several alternatives being carried out in successive stages.

1.4. Scoring the alternatives depending on the criteria

The scores are granted for n alternatives, based on the m -1 criteria (remained after the zero criterion is eliminated) and it is carried out successively on the criteria, in two stages: *primary scores and normalized scores*.

Primary scores. Regarding the C_i criterion, for each V_j alternative, primary scores $N^*_{i,j}$ are granted, by one of the following procedures:

a. If the alternatives can be characterized by a quantifiable measure unit, $M_{i,j}$, in direct ratio to the advantages of the effects (for instance, the investment cost, the operation costs etc.), the primary scores shall be:

$$N^*_{i,j} = \frac{M_{i,j}}{\sum_{j=1}^{n} M_{i,j}} \quad (1)$$

If the alternatives can be characterized by a quantifiable measure unit, $M_{i,j}$, in reversed ratio to the advantages:

$$N^*_{i,j} = \frac{\frac{1}{M_{i,j}}}{\sum_{j=1}^{n} \frac{1}{M_{i,j}}} \quad (1\ bis)$$

b. If the alternatives can not be characterized by a quantifiable measure unit, the primary scores shall be granted by estimation, in accordance with one of the following procedures:

b.1. By granting scores from 0 to 10, thus:

– if the effects of all the alternatives are benefic (advantageous for the environment), or if the effects of all the alternatives are malefic (disadvantaging the environment), the most advantageous alternatives shall receive the highest scores;

– if the effects of the alternatives are benefic or malefic, the most advantageous alternatives shall receive scores from 6 to 10, the disadvantageous one from 0 to 4, and the neutral ones, 5;

b.2.If adequate, the primary scores may be established by the procedure used to establish the criteria percentage (according to paragraph 1.2.), where the C_i criteria shall be substituted by all the V_j alternatives; the values of the $N^*_{i,j}$ primary scores shall be equal to the ones corresponding to the p_i criteria percentage, from the previously mentioned case.

Normalized scores. Because the criteria importance is expressed by their percentage, p_i, the sum of the scores granted to all the alternatives for any of the C_i criteria must be the same; otherwise, the scores level may alter the criteria importance and, thus, the alternatives classification, possibly based on minor criteria, shall contradict the classification based on the major criteria. For instance, if for one criterion, all the alternatives receive a 10, and for another, all receive a 5, the score for the first criterion shall be double, although it can be less important than the second one.

That is why, the scores for a criterion must be normalized so their sum, on the n alternatives, is the same, for instance equal to 1. This may be achieved by defining the $N_{i,j}$ normalized scores according to the following formula:

$$N_{i,j} = \frac{N^*_{i,j}}{\sum_{j=1}^{n} N^*_{i,j}} \tag{2}$$

which, automatically, complies with the condition:

$$\sum_{j=1}^{n} N_{i,j} = 1 \tag{3}$$

Regarding the primary scores granting 1, the condition is implicitly achieved, the primary scores being identical to the normalized scores.

1.5. Scores calculation

After completing the scoring for all the alternatives and based on all the criteria, the next operations are:

Calculation of the weighted scores:

$$\left(N_{i,j}\right)_p = N_{i,j} \cdot p_i \tag{4}$$

– Summing the weighted scores for each V_j alternative, based on all the C_i criteria, thus resulting the total score per alternative:

$$N_j = \sum_{i=1}^{m-1} N_{i,j} \cdot p_i \tag{5}$$

This score relatively characterizes the analyzed alternatives, based on all the adopted criteria.

– To highlight the differences between the alternatives it is useful to calculate, also, the relative total score per each alternative:

$$\left(N_j\right)_R = \frac{N_j}{\sum_{j=i}^{n} N_j} \tag{6}$$

The calculation is organized as table, according to the following model

C_i	p_i	V_1			V_j			V_n	
		$N_{i,1}$	$N_{i,1} \cdot p_i$	...	$N_{i,j}$	$N_{i,j} \cdot p_i$	...	$N_{i,n}$	$N_{i,n} \cdot p_i$
C_1	p_1			...			...		
C_2	p_2								
C_{m-1}	p_{m-1}			...			...		
TOTAL	-	-	N_1	...	-	N_j	...	-	N_n

1.6. Decision making

Mainly, the alternative with the highest total score is preferred. Taking into account the various subjective estimations and the relativity of certain primary information (database), the score differences between the alternatives which are under 10% (under 0,1 differences between the total relative scores) must not be considered as decisive. Under such circumstances, details or additional studies must be obtained, or additional criteria must be introduced, or one of the 10 different scored alternatives is selected based on the main decision maker preference criteria. This main decision maker is also responsible for the approval of the investment.

To downsize the subjectivity degree when calculation the scores, it recommended that the multi-criteria decision methodology be applied by several decision makers, who will independently record the effects even if the formal aspects are conducted by the same operator [3]. This procedure is applied sometimes, but, in practice, due to the relatively large volume of work, one decision maker is used.

2. A study case - Tailings Management Facilities (TMF)

2.1. General

The Certej project is located within the Apuseni and Metaliferi mountains of Romania. The processing of the Certej ore deposit will be undertaken in two stages: ore flotation, producing gold concentrate and flotation tailings and oxygen leaching (Albion process) followed by CIL leaching of oxidized concentrate and gold and silver recovery. The products resulted are ore alloy and cyanidation tailings (CIL tailings). The two types of tailings (flotation and CIL) will be stored in two separated Tailings Management Facilities [4].
The Flotation TMF includes the construction of one cross valley embankment and one saddle embankment while the CIL TMF includes the construction of a cross valley embankment.
The Flotation TMF will be required to house 40.5 million tones of tailings during mining life. In the area of the project were found two possible locations with certain advantages and disadvantages. Selection of the most advantageous option is presented in the followings.

2.2. Selected alternatives

Based on in site studies and design requirements two alternatives were selected [5]. Thei locations are shown in figure 1.

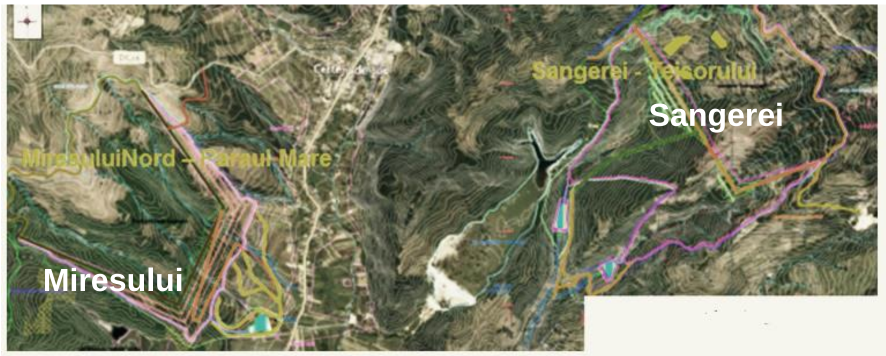

Fig. 1. Location of the alternatives

2.2.1. Alternative 1. Sangerei

The main dam closes the valleys of Singerei and Teisorului at the crest level 480.0 mASL. On the right slope a secondary dam has to be built in order provides the retention at 480.0 mASL, due to the geomorphology of the land.
The body of the main dam and of the secondary closure dam are made of local materials, from the barren rocks resulting from the excavation and exploitation of

the ore quarry. These sterile rocks will continue to be referred to in the paper as "sterile dump".
The starter dam provides the required volume for deposition of tailings in the first 2 years of operation of the ore preparation plant. The crown elevation of the starter dam is 420.0 mASL The starter dam is a clay core rockfill dam.

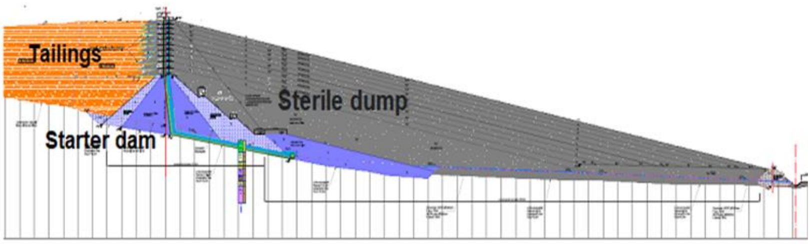

Fig. 2. Main cross section of Sangerei TMF.

Table 1. Sangerei TMF parameters

Total investment cost:	396.455.779 USD
Investment in stage 1- Starter	98.945.905 USD
Excavation volume: 7.056.794 m3	
Fillings volume: 54.455.833 m3	
Maximum dam height: 125m	
Area: 2.90 kmp	
Final tailings storage: 39.616.620 m^3; 29.316.299 tone	

2.2.2. Alternative 2 Miresului

The tailings dam body is made of rockfill obtained from several rockfill quarries. Two lateral dams one on the left bank and the another one on the right bank create the deposition volume. The starter dam is a rockfill dam with a membrane face

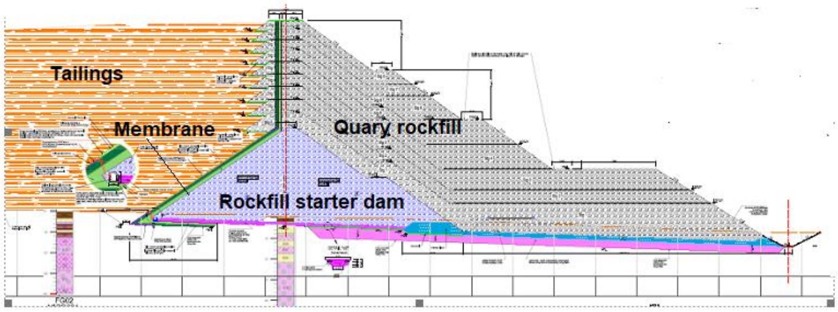

Table 2. Miresului TMF parameters

Total investment cost:	215.927.566 USD
Investment for stage 1 – Starter:	47.056.792 USD
Excavation volume:	4.148.532 m3
Deposition volume:	15.848.460 m3
Maximum dam height: 100m	
Total area: 2.22 kmp	
Final tailings storage**:**	42.333.314 m^3; 31.326.652 tone

2.3. Establishing the criteria

The **first criterion**, involved in any selection process, is the **investment cost**. The cost of investment for the starter dam has to be a distinct sub criterion since the financial effort is part of the construction stage. The staged heightening's that follows are part of the operation costs. The investment costs include beside the ones related to dams the cost of the access roads and the cost of TMF closure at the end of mine operation.

Table 3. Investment cost

Alternative	Investment for starter dam (USD)	Investment cost of the dam erected (USD)	Cost of the accesses roads (USD)	Cost of the closure works (USD)
Sangerei	**98.945.905**	**396.455.779**	**10.853.252**	**11.706.516**
Miresului	**47.056.792**	**215.927.566**	**9 .681.301**	**9.778.051**

The **second criterion** is the **safety** during the operation. The TMF safety implies the dam stability, the safe water management even during floods, and the probability of the failure mechanism during all phases of the facility operation.

The **third criterion** is **the technique of raising in stages** according to deposition progress. The time required to built the starter dam is of paramount importance since its s a mandatory condition for staring the process plant. The time schedule for starter construction depends on the climate condition. For the clay core the construction has to stop during the winter and during the heavy rains. Providing some volume for the barren rocks resulting from the excavation and exploitation of the ore quarry is in favor of the alternative.

The **fourth criterion** is the environmental impact during TMF operation and then TMF closure. The quantifying parameters are the area covered by tailings, number of river beds affected, the distance from human settlements, control of chemical composition of tailings and the impact of the TMF after closure.

Based on the above considerations several sub-criteria were defined in order to differenced the two TMF locations.

Table 4. Criteria and subcriteria

C1. Investment cost	**C11** Overall cost (dam, water management, closure)	**C2. Safety**	**C21** Structural stability
	C12 Starter investment cost		**C22** Water and flood management (resistance to overtopping included)
	C13 Investment required by main roads and access roads		**C23** Failure probability
	C14 Investment for closure and post management		**C24** "zero" fictive criterion
	C15 "zero" fictive criterion		
C3 Construction schedule	**C3**1 Duration of starter building	**C4 Environment impact**	**C41** Total area affected
	C32 Observing the raising stages schedule		**C42** Number of affected water courses
	C33 Flexibility in deposition		**C43** Distance from human settlements
	C34 Volume provided for barren rocks deposition		**C44** Water pollution during the plant operation and after closure
	C35 "zero" fictive criterion		**C45** "zero" fictive criterion

2.4. Ranking and establishing the criteria percentage

The ranking of criteria and their weights was achieved based on brain-storming including designer, environment agency and the owner.

Table 5. Weights of the main criteria

Criterion	**C1**	**C2**	**C3**	**C4**	**C5**
Investment cost - C1		**1**	**1**	**1**	**0**
Safety - C2	**1**		**0**	**1**	**0**
Construction schedule - C3	**1**	**2**		**2**	**0**
Environment impact - C4	**1**	**1**	**0**		**0**
„zero" – C5	**2**	**2**	**2**	**2**	
Total	**5**	**6**	**3**	**6**	**0**
Weights	**0,25**	**0.30**	**0,15**	**0.30**	**0**

$p_1 = 0,25$; $p_2 = 0,30$; $p_3 = 0,15$; $p_4 = 0.30$

$\Sigma p_i = p_1 + p_2 + p_3 + p_4 = 1$

Table 6. Weights of the subcritera of C1

Criterion	**C11**	**C12**	**C13**	**C14**	**C15**
Overall cost (dam, water management, closure) - **C11**		**1**	**0**		
Starter investment cost – **C12**	**1**		**0**	**0**	**0**
Investment required by main roads and access roads – **C13**	**2**	**2**		**1**	**0**
Investment for closure and post management - **C14**	**2**	**2**	**1**		**0**
„zero" – C15	**2**	**2**	**2**	**2**	
Total	**7**	**7**	**3**	**3**	**0**
Weights	**0, 35**	**0,35**	**0.15**	**0.15**	**0**

$p'_{11} = 0{,}35$; $p'_{12} = 0{,}35$; $p'_{13} = 0.15$; $p'_{14} = 0.15$

$p'_{11} + p'_{13} + p'_{12} + p'_{14} = 1$

Since the weight of C1 is 0.34 final weights are:

$p_{1.1} = 0{,}35 \cdot 0{,}25 = 0{,}0875$; $p_{1.2} = 0{,}35 \cdot 0{,}25 = 0{,}0875$; $p_{13} = 0{,}15 \cdot 0{,}25 = 0{,}0375$

$p_{14} = 0{,}15 \cdot 0{,}25 = 0{,}0375$ $p_{1.1} + p_{1.2} + p_{13} + p_{14} = 0{,}25$

Table 7. Weights of the subcritera of C2

Criterion	**C21**	**C22**	**C23**	**C24**
Structural stability - **C21**		**0**	**1**	**0**
Flood management - **C22**	**2**		**1**	**0**
Failure probability - **C23**	**1**	**1**		**0**
„zero" – **C24**	**2**	**2**	**2**	
Total	**4**	**3**	**4**	**0**
Weights	**0.36**	**0.27**	**0.37**	

$p'_{2.1} = 0{,}36$; $p'_{2.2} = 0{,}27$; $p'_{2.3} = 0{,}37$ $p'_{1.1} + p'_{1.2} + p'_{2.3} = 1$

Since the weight of C2 is 0.30 final weights are:

$p_{2.1} = 0{,}30 \cdot 0{,}36 = 0{,}108$; $p_{2.2} = 0{,}30 \cdot 0{,}27 = 0{,}081$; $p_{2.3} = 0{,}30 \cdot 0{,}37 = 0{,}111$

$p_{2.1} + p_{2.2} + p_{2.3} = 0{,}30$

Table 8. Weights of the subcritera of C3

Criteri0n	C31	C32	C33	C34	C35
Duration of starter construction – **C31**		1	0	1	0
Observing the schedule of heightening's - **C32**	1		0	0	0
Flexibility of depositions - **C33**	2	2		1	0
Volume available for sterile dump - **C34**	1	2	1		0
"zero" - **C35**	2	2	2	2	
Total	**6**	**9**	**3**	**3**	**0**
Weights	**0,286**	**0,428**	**0.143**	**0.143**	

$p'_{3.1} = 0{,}286$ $p'_{3.2} = 0{,}428$ $p'_{33} = 0{,}143$ $p'_{3.4} =$

$= 0{,}143$ $p'_{3.1} + p'_{3.2} + p'_{3.3} + p'_{3.4} = 1$

Since the weight of C3 is 0.15 final weights are:

$p_{3.1} = 0{,}15 \cdot 0{,}286 = 0{,}0429$; $p_{3.2} = 0{,}15 \cdot 0{,}428 = 0{,}0642$ $p_{3.3} = 0{,}15 \cdot 0{,}143 = 0{,}02145$
$p_{3.4} = 0{,}15 \cdot 0{,}143 = 0{,}02145$ $p_{3.1} + p_{3.2} + p_{3.3} + p_{343} = 0{,}15$

Table 9. Weights of the subcritiera of C4

Criterion	C4 1	C42	C43	C44	C45
Area of footprint – **C 41**		1	0	1	
Number of affected water courses – **C42**	1		1	1	
Distance from human settlements – **C43**	2	2		1	
Water pollution during the plant operation and after closure – **C44**	1	1	1		
"Zero" – **C45**	2	2	2	2	
Total	**6**	**6**	**4**	**5**	
Weights	**0,285**	**0,285**	**0,19**	**0.24**	

$p'_{4.1} = 0{,}285$; $p'_{4.2} = 0{,}285$ $p'_{4.3} = 0{,}19$ $p'_{4.4} = 0{,}24$ $p'_{4.1} + p'_{4.2} + p'_{4.3} = 1$

Since the weight for C4 is 0.30

$p_{4.1} = 0{,}285 \cdot 0{,}30 = 0{,}085$; $p_{4.2} = 0{,}285 \cdot 0{,}30 = 0{,}086$; $p_{4.3} = 0{,}19 \cdot 0{,}30 = 0{,}057$

$p_{4.4} = 0{,}24 \cdot 0{,}30 = 0{,}072$

$p_{4.1} + p_{4.2} + p_{4.3} = 0{,}30$

Table 10. Weights of criteria and sub criteria

Criterion	Weight	Sub - criterion	Weights per criteria - p'	Total weight p
Investment cost - **C1**	0,25	Total investment cost- **C11**	0,35	0,0875
		Investment cost - starter – **C12**	0,35	0,0875
		Investment required by main roads and access roads – **C13**	0,15	0,0375
		Investment for closure and post management **- C14**	0.15	0,0375
Safety - **C2**	0,30	Structural safety - **C2**1	0,36	0,108
		Flood management - **C22**	0.27	0,081
		Failure probability - **C23**	0,37	0,111
Construction schedule - **C3**	0,15	Duration of starter construction - **C31**	0,286	0,0429
		Observing the schedule of heightening's - **C32**	0,428	0,0642
		Flexibility of depositions – **C33**	0.143	0.0214
		Volume available for sterile dump - **C34**	0.143	0.0214
Environment impact – **C4**	0,30	Affected area - **C41**	0,285	0,0855
		Number of affected water courses - **C42**	0,285	0,0855
		Distance from human settlements - **C43**	0,19	0,057
		Water pollution during the plant operation and after closure – **C44**	0.24	0.072
TOTAL	**1**			**1**

2.5. Scoring the alternatives depending on the criteria

2.5.1. Criterion 1 – Investment cost

Primary scores are based on investment for each of the two alternatives and are evaluated with relationship (1):

$$N^*_{i,j} = \frac{\frac{1}{M_{i,j}}}{\sum_{j=1}^{n} \frac{1}{M_{i,j}}}$$

were $M_{i,j}$ is the investment corresponding to alternatives (i – criterion, j –

alternative). The advantage is on the low cost. (1/M). Primary scores of the sub-criteria for the C1 criterion are:

Table 11. Scores of the sub-criteria for the C**1**

Sub- criterion		**Alternatives**	
		V1 Sangerei -	**V2 Miresului**
C11 – overall cost.	**Investment ($M_{i,j}$)** 10^3 USD / 1/M	**396.455** (0.00252)	**215.927** (0.004651)
	Primary score N*	0,3514	0.6485
C12 - Starter	**Investment ($M_{i,j}$)** 10^3 USD / 1/M	**98.945** (0.0102)	**47.056** (0.02127)
	Primary score N*	0,3241	0.6758
C13 - roads	**Investment ($M_{i,j}$)** 10^3 USD / 1/M	10.853 (0.09214)	9 .681 (0.1033)
	Primary score N*	0.4714	0,5285
C14 - Investment for closure and post management	**Investment ($M_{i,j}$)** 10^3 USD / 1/M	11.706 (0.08542)	9.778 (0.10227)
	Primary score N*	0.4551	0,5449

2.5.2. Criterion C2 - Safety

Since there is not a quantitative measure of safety criteria the alternatives are appreciated by means of primary scores (in the range 1 to 10). The minimum score in the case of favorable appreciation is 6.

Subcriterion C21 – Structural safety. The safety of the rockfill tailings dam (Miresului) is significantly larger comparing to the tailings dam raised in stages by using sterile dump with heterogeneous materials partly un compacted (Sangerei). The primary scores are normalized by relationship (2):

$$N_{i,j} = \frac{N^*_{i,j}}{\sum_{j=1}^{n} N^*_{i,j}}$$

Subcritiron C22 – Flood management. Both alternatives are provided with a volume capable to store the flood volume. The volume is created between the deposition elevation and crest elevation at a certain raised stage. Assuming an adverse situation (the water level in the pond is larger than the one that is specified by operation rules or the crest level is not completely achieved for the raising stage) an overspill is expected. The overflowing of the rockfill body (Miresului) can be supported with minor effects but overflowing of the downstream shell made of uncompacted materials (Sangerei) leads to severe external erosion and failure.

Subcriterion C23 – Failure probability. A failure probability evaluation is rather difficult at the design stage since the variables involved in the analysis are significantly dependent on the existing structure and its in time behavior. Consequently, the failure probabilities were assumed similar to the ones for water storage dams [6]. They are 10^{-6} for the rockfill dams with upstream sealing

(corresponding to Miresului) and 10^{-5} for homogeneous earth fill dams (corresponding to Sangerei).
Based on the above considerations the primary sc0res and the normalized ones are presented in table 12.

Table 12. Scores of the sub-criteria for the C**2**

Sub- criterion		**Alternatives**	
		V1 Sangerei	**V2 Miresului**
C21 – structural safety	Primary score	6	9
	Normalized score	0.4	0.6
C22 – Flood management	Primary score	6	10
	Normalized score	0.375	0.625
C23 – Failure probability	Primary score	6	9
	Normalized score	0.4	0.6

2.5.3. Criterion C3 – Construction schedule

Subcriterion C31 - Duration of starter building. The time interval required for building the starter dam depends on dam type selected as starter. The construction of the clay core embankment dam with a thick core (Sangerei) has major impediments during the winter season and during heavy rains. Consequently, the duration of the dam construction is quite large and the ore processing is delayed. On the contrary, the construction of the rockfill dam with upstream sealing (Miresului) can be performed all the year round.
Subcriterion C32 - Observing the raising stages schedule. The staged construction of TMF has to provide space for tailings deposition according to the rate of ore processing. Random embankment of the downstream shell (Sangerei) is season dependent and has to be stopped during frozen temperatures and heavy rains. In case of such events the rate of ore processing is affected. By using the rockfill as construction material for dam raising the construction can proceed according to schedule even in climate constrains.
Subcriterion C33 - Flexibility in deposition. The layout of Miresului alternative closes two valleys and consequently the deposition of tailing and dam raising can be made independent for each of them according to needs of volumes.
Subcriterion C34 - Volume provided for barren rocks deposition. Sangerei alternative uses the barren rocks for downstream shell raising. In the case of Miresului alternative a separate area and efforts are required for dumping the barren rocks.
Based on the above considerations the primary scores and the normalized ones are presented in table 13.

Table 13. Scores of the sub-criteria for the C**3**

Sub- criterion		**Alternatives**	
		V1 Sangerei	**V2 Miresului**
C31 - Duration of starter building.	Primary score	3	9
	Normalized score	0.25	0.75
C32 - Observing the raising stages schedule.	Primary score	4	9
	Normalized score	0.307	0.693
C33 - *Flexibility in deposition.*	Primary score	6	9
	Normalized score	0.4	0.6
C34 - *Volume provided for barren rocks deposition.*	Primary score	9	1
	Normalized score	0.9	0.1

*2.5.4. Criterion C*4 - Environment impact

Subcriterion C41 - Total area affected. Scoring is based on the areas occupied by the alternatives $S_{i,j}$ by using the relationship (1)

were $S_{i,j}$ is the area of the alternative (the larger area the more unfavorable effect of the alternative)

Alternatives	Occupied area (Km^2)	Primary score N*
V1 Sangerei	0.933 (1.072)	**0.208**
V2 Miresului	0.647 (1.5456)	**0,409**

Subcriterion C42 - Number of affected water courses. The alternative Miresului is built on two valleys and the environmental effect is larger

Subcriterion C43 - Distance from human settlements. In the case of Miresului location the distance from Certeju de Sus is less than 1.0 km. On the other hand, in the case of the Sangerei location, there is the danger of the opposition from the local community of the village of Nojag, which will lead to the blocking of the project. Consequently, a tie cannot be made based on this sub-criterion.

Subcriterion C44 - Water pollution during the plant operation and after closure. Acidic drainage is the main source of water contamination. This phenomenon is potentiated by the tailings surface exposed at the downstream face in the case of Sangerei site and is greatly reduced in the case of the Miresului site where the downstream shell is made of rockfill.

Based on the above considerations the primary scores and the normalized ones for C42 - C44 subcriteria are presented in table 14.

$$S_{i,j}^{*} = \frac{\frac{1}{S_{i,j}}}{\sum_{j=1}^{n} \frac{1}{S_{i,j}}}$$

Table 14. Scores of the sub-criteria for the C4

Sub- criterion		**Alternatives**	
		V1 Sangerei -	**V2 Miresului**
C42 – *Number of affected water courses*	Primary score	1	2
	Normalized score	0.66	0.33
C43 - Distance from human settlements	Primary score	5	5
	Normalized score	0.5	0.5
C44 - Water pollution during the plant operation and after closure	Primary score	2	8
	Normalized score	0.2	0.8

2.6. Scores evaluation

After completing the scoring for all the alternatives and based on all the criteria, the next operations are:

– Calculation of the weighted scores relationship (4):

$$\left(N_{i,j}\right)_p = N_{i,j} \cdot p_i$$

– Summing the weighted scores for each V_j alternative, based on all the C_i criteria, thus resulting the total score per alternative (relationship (5):

$$N_j = \sum_{i=1}^{m-1} N_{i,j} \cdot p_i$$

that characterizes the alternatives.

In order to highlight the differences between the alternatives it is useful to calculate, also, the relative total score per each alternative (relationship (6):

$$\left(N_j\right)_R = \frac{N_j}{\sum_{j=i}^{n} N_j} \qquad (7)$$

The results are presented in the table 15.

Table 15. Scores per alternatives

Criteri	**Weight**	**Sub-criterion**	**Total weight p**	**V1 Sangerei -**		**V2 Miresului**	
				Normalized score	Relative total score	Normalized score	Relative total score
Investment cost **C1 - C1**	0,25	Overall cost - **C11**	0,0875	0.3514	0.03075	0.6485	**0.05674**
		Starter investment cost – **C12**	0,0875	0.3241	0.02836	0.6758	**0.05913**
		Investment main roads and access roads – **C13**	0,0375	0.4714	0.0176	0.5285	**0.02043**
		Investment for closure and post management -**C14**	0,0375	0.4551	0.01706	0.5449	**0.02043**
Safety C2	0,30	Structural stability - **C21**	0,108	0.4	0.0432	0.6	**0.0648**
		Water and flood management - **C22**	0,081	0.375	0.0303	0.625	**0.0506**
		Failure probability- **C23**	0,111	0.4	0.044	0.6	**0.0666**
Construction schedule **C3 - C3**	0,15	Duration of starter building - **C31**	0,0429	0.25	0.01072	0.75	**0.03217**
		Observing the raising stages schedule - **C32**	0,0642	0.307	0.01971	0.693	**0.04449**
		Flexibility in deposition – **C33**	0.0214	0.4	0.00856	0.6	**0.01284**
		Volume provided for barren rocks deposition – **C34**	0.0214	0.9	0.01926	0.1	**0.00214**
Environment impact **C4 – C4**	0,30	Total area affected - **C41**	0,0855	0.208	0.01778	0.409	**0.0349**
		Number of affected water courses - **C42**	0,0855	0.66	0.05643	0.3	**0.0256**
		Distance from human settlements - **C43**	0,057	0.5	0.0285	0.5	**0.0285**
		Water pollution – **C44**	0.072	0.2	0.0144	0.8	**0.0576**
TO-TAL	**1**		**1**		**0.38663**		**0.57697**

2.7. Alternative selection

Based on total score it turns out that alternative 2, the location of Miresului is clearly advantageous both in the multi-criteria comparison and on individual criteria. The percentage score is 60% versus 40% in favor of the Miresului location. The advantage of the V2 alternative is created by the economic criterion and by the safety criterion, that is essential in all authorization phases.

3. Concluding remarks

Multicriteria analysis or multiobjective decision making is a type of decision analysis tool that is particularly applicable to cases where a single-criterion approach (such as cost-benefit analysis) falls short, especially where significant environmental and social impacts cannot be assigned monetary values. MCDA allows decision makers to include a full range of social, environmental, technical, economic, and financial criteria.

The TMF site selection case presented in the paper illustrates the applicability of the approach. Each alternative is represented by its performance in multiple criteria. The problem may be defined as finding the best alternative for a decision-maker. Explicit recognition is given to the fact that a variety of both monetary and nonmonetary objectives may influence policy decisions.

References

[1] Huang I.B., Keisler J., Linkov I., *Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends*, Science of the total environment, Elsevier, 2011.

[2] Cegan J.C., Filion A.M., Keisler J.M., Linkov I., *Trends and applications of multicriteria decision analysis in environmental sciences: literature review*, Environment Systems, Springer, 2017.

[3] Adem Esmail B., Geneletti D., *Multi-criteria decision analysis for nature conservation: A review of 20 years of applications*, Methods in Ecology and Evolution, Wiley Online Library, 2018.

[4] Golder Associates. Certej Gold Project. T2 Tailings Management Facility Key Issues and Design Approach, 2017.

[5] RUXPRO. 2017. T2 Tailings Management Facility (TMF) Sangerei-Teisorului Perimeter, Miresului Nord-Valea Mare Perimeter. Final Report. Documentation: 87.HD-DG.SPF.05/2017

[6] World Commission on Dams Report. Integrated Decision-Making Framework. (http:// www.dams.org/report/contents.htm).