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A Multicriteria Decision Analysis Approach for Selection of Remedial Alternatives at Mine Sites

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Abstract The selection of remedial alternatives for mine sites is a complex task because it involves multiple criteria and often with conflicting objectives. However, an existing framework used to select remedial alternatives lacks multicriteria decision analysis (MCDA) aids and does not consider uncertainty in the selection of alternatives. The objective of this paper is to improve the existing framework by introducing deterministic and probabilistic MCDA methods. A case study was presented to demonstrate the improved framework at a mine site. The results showed that the improved framework provides a reliable way of selecting remedial alternatives as well as quantifying the impact of different criteria on selecting alternatives.

Keywords MCDA, PROMETHEE, Probabilistic PROMETHEE, Remedial alternatives

Introduction

Remedial alternatives are important to control the impacts of Acid Rock Drainage (ARD) caused by the considerable amounts mine waste rocks. However, selecting the optimal alternatives for a mine site is quite complex (USEPA 2006). This is because most environmental decision-making involves multiple and conflicting objectives such as minimizing risk and cost, maximizing benefit, and maximizing stakeholder preferences (Kiker *et al.* 2005; Sadiq and Tesfamariam 2009). Moreover, input information for each objective is often obtained in different forms (*i.e.* quantitative and qualitative), which are non-commensurable and thus exacerbate the decision making process (Tsfamariam and Sadiq 2008).

An existing framework (USEPA 1988) for selecting remedial alternatives at mine sites consists of scoping, site characterization, treatability investigations, development and screening of alternatives, detailed analysis of alternatives, and selection of optimum alternative. In this framework, experts conduct remedial selection analysis without multiple criteria decision analysis (MCDA) aids. However, the literature shows that humans are not ca-

pable of solving multiple objectives unaided. When they attempt to do so, opposing views are often discarded (McDaniels *et al.* 1999).

Multicriteria decision analysis (MCDA) methods deal with a problem whose alternatives are predefined and decision-makers rank available alternatives based on the evaluation of multiple criteria (Tsfamariam and Sadiq 2006). For environmental decision making, the commonly used MCDA methods include utility theory and outranking (Belton and Stewart 2002; and Figueria *et al.* 2005). Utility theory methods use a utility/value function for each criterion to evaluate alternatives and to aggregate the utility/value of each criterion in order to identify the best alternative (Keeney and Raiffa 1993). On the other hand, the outranking methods build an outranking relation and then exploit this relation to identify the best alternative, sort alternatives into groups, or rank them (Belton and Stewart 2002).

Uncertainty is an unavoidable and inevitable component of any environmental decision making process (Sadiq and Tesfamariam 2009). MCDA methods require input data such as weights of criteria and preference of alter-

natives with respect to each criterion provided by decision makers. However, these data have uncertainty because of decision makers’ judgment and subjectivity. Before informed decisions can be made, this uncertainty must be quantified, through the application of available techniques. Therefore, the objective of this paper is to improve the existing framework used for selecting remedial alternatives by introducing deterministic and probabilistic MCDA methods.

Method

The proposed framework

The proposed framework for selecting remedial alternatives is shown in Fig. 1. This framework improves the existing one by introducing deterministic and probabilistic multicriteria decision analysis methods instead of “Detailed Analysis of Alternatives” block. Moreover, the proposed framework introduces “Result Analysis” block. The deterministic multicriteria block consists of identifying criteria to evaluate alternatives,

identifying the weight of criteria using analytical hierarchical process (AHP), and applying Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) I and II methods, which are an outranking MCDA method. The probabilistic multicriteria decision analysis block consists of identifying criteria to evaluate alternatives, defining the weight of criteria by using AHP, defining probability distribution for the weight of criteria, conducting Monte Carlo Simulation, applying PROMETHEE II, and conducting a sensitivity analysis.

The PROMETHEE I and II methods are multicriteria decision making techniques developed by Brans *et al.* (1986). These methods build a valued outranking relation and exploit this relation to obtain a partial ranking (PROMETHEE I) or complete ranking (PROMETHEE II). AHP is one of the MCDA methods that assists decision makers in solving complex problems by organizing thought, experiences, knowledge, and judgments into a hierarchical framework, and by guiding them through a sequence of pairwise comparison judgments (Saaty 1982). The detail description of AHP and PROMETHEE methods can be seen in Betrie *et al.* (2013).

Case study

Site characterization information was obtained from the closure plan report of the mine site. The remediation objective at this mine site is to reduce environmental risk. The maximum environmental concentration in soil and groundwater was obtained from a steady state equivalence-based model developed for this mine site by Betrie *et al.* (2012). The tailings and waste rocks are sources of copper metal emissions. Intermedia transport through diffusion and advection were considered. The environmental risk was estimated using the Hazard Quotient (HQ) approach (USEPA 1997). HQ is estimated as a ratio of maximum environmental contaminant concentration and the screening benchmark value, which is a No-Adverse Effects Level con-

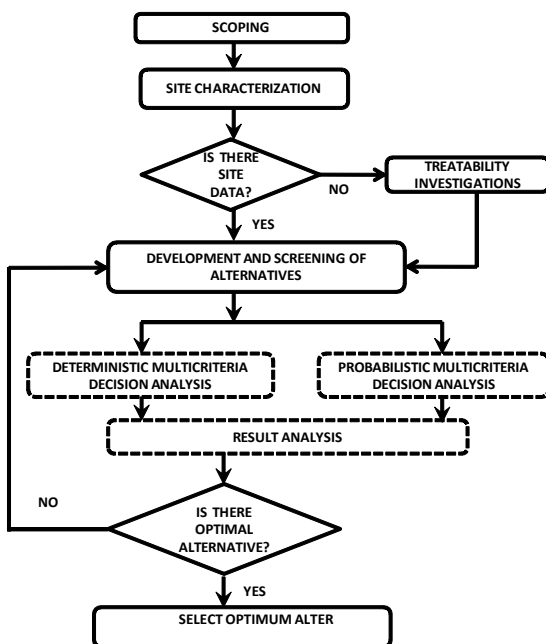


Fig. 1 Proposed framework for selecting remedial alternatives at mine sites.

centration obtained from a regulatory agency. Note that for a calculated value of $HQ > 1$ indicates harmful effects cannot be ruled out; if $HQ = 1$, contaminant alone is not likely to cause ecological risk; and if $HQ < 1$, harmful effects are not likely (USEPA, 1997).

Alternatives and their effectiveness to reduce contaminants were obtained from literatures. The alternatives are Do-nothing (DN), Soil Cover (SC), Membrane System (MC), Water cover (WC), Water cover (WC), Excavation and On-site disposal (EON), Excavation and Off-site disposal (EOF), Water Treatment (WT), Constructed Wetland (CW), and Sulphate Reducing Bacteria (SB). The effectiveness of DN=0 %, SC=33 % (MEND 1999a), MC=70 % (Meek 1994), WC=99 % (Vigneault *et al.* 2007; Yanful & Simms 1997), EON=99 % (USEPA 1995), EOF=99 % (USEPA 1995), WT=90 % (USEPA 1995), CW=30 % (MEND, 1999b; Skousen *et al.* 1998), and SB=80 % (USEPA 2006).

Criteria to evaluate the alternatives were identified in order to in ensure that the proposed remedial objectives are achieved. These criteria are minimize risk posed to fish (Risk), minimize the cost of an alternative (Cost), maximize the short-term performance of an alternative (SP), maximize the long-term performance of an alternative (LP), maximize the implementability of an alternative (IM), maximize the reduction of toxicity (RT), and maximize the future of the mine site (FU). Each criterion except risk was rated by experts on a

scale of 1 to 9. An alternative that has low cost rated as 9 and the high cost rated as 1. For short-term performance, an alternative that has immediate effect after implementation is rated as 9 and an alternative that would take a longer time to be effective is rated as 1. For long-term performance, an alternative that is effective for longer durations is rated as 9; otherwise, it is rated close to 1. If an alternative is easy to implement, it is rated as 9; otherwise, it is rated at a lesser value. An alternative that has an excellent effect on the reduction, mobility, and transport of contaminants is rated as 9; otherwise, it is rated at a lesser value. An alternative that would increase future use and aesthetic of the site is rated as 9.

The input information for deterministic multicriteria method should be provided as an evaluation table as shown in Table 1. This evaluation table consists of criteria; whether the criteria have to be minimized or maximized; criteria weight that shows relative importance one criterion over other criteria; the alternatives' evaluation outcome with respect to each criterion; preference function that gives the degree of preference of an alternative against another alternative; and preference parameter value that has to be fixed. The criteria weights were obtained from the AHP computation. The obtained results of AHP show that Risk is the most prioritized (*i.e.* 0.41) criterion followed by Cost, LP, RT, IM, FU, and SP. Type III (*i.e.* V-shape) preference function was selected

Criteria	Min or Max	Criteria weight	Criteria										Preference function	Preference parameter
			DN	SC	MC	WC	EON	EOF	WT	CW	SB			
Risk	min	0.41	260	174	78	13	2.6	0	26	182	52	III	230	
Cost	min	0.23	1	6	9	3	8	9	8	3	3	III	8.8	
SP	max	0.02	1	2	2	9	6	8	9	4	7	III	8.8	
LP	max	0.16	1	5	7	8	9	9	6	7	4	III	8.8	
IM	max	0.06	9	5	2	8	7	7	5	8	9	III	8.8	
RT	max	0.08	1	4	4	6	8	9	8	3	5	III	8.8	
FU	max	0.04	1	4	6	5	8	9	2	7	1	III	8.8	

Table 1 Evaluation table for deterministic PROMETHEE analysis.

for all criteria. This preference type was selected because it best represents the data compared to other preference functions. The parameter value of type III function that was assumed for the Risk criterion was equal to 230 and for the other criteria was equal to 8.8.

The input information for the probabilistic multicriteria method should be provided similar to Table 1, but the uncertainty associated with weight of criteria should be quantified using the probabilistic technique. A uniform probability distribution function was defined for the weights of criteria. Inputs to this distribution were defined by multiplying the original weight of each criterion by $\pm 10\%$. Each probability distribution was randomly sampled 5000 times using the Monte Carlo Simulation (MCS) technique. For each combination of randomly sampled weight, the MCDA method (PROMETHEE II) was run.

The results of criteria weights and PROMETHEE II outputs obtained from 5000 MCS run were ranked and then correlation coefficients were estimated using the Spearman rank correlation method. The estimated correlation coefficients of each alternative and criterion were normalized and multiplied by 100 to obtain the contribution (in percent) of the criteria on overall ranking of the alternatives.

Results and discussion

The results of deterministic partial (PROMETHEE I) showed that the WC alternative dominates all the alternatives. The SB alternative dominates all the alternatives except WC and EOF; the SB alternative is dominated by WC and is incomparable with EOF. The EOF alternative dominates the DN, SC, MC, WT and CW alternatives, is dominated by WC alternative, and is incomparable with the SB and EON alternatives. The EON alternative dominates the DN, SC, MC and CW alternatives, is dominated by the WC and SB alternatives, and is incomparable with EOF and WT. The WT alternative dominates the DN, SC, and CW alternatives, is dominated by the WC, SB, and EOF alternatives, and is incomparable with the

EON and MC alternatives. The CW alternative dominates the DN and SC alternatives, is incomparable with MC, and is dominated by the WC, SB, EOF, EON and WT alternatives. The DN and SC alternatives are incomparable. The alternatives are incomparable whenever they have conflicting relative rankings. Incomparability between the alternatives occurs if an alternative is superior according to some criteria and inferior according to other criteria compared to other alternatives. For instance, the incomparability of SB and EOF occurs because the EOF alternative performs better on the Risk, LP, RT and FU criteria than does the SB alternative, whereas the SB alternative performs better on Cost and IM criteria.

The results of deterministic complete ranking (PROMETHEE II) revealed that WC ranked first followed by the SB, EOF, EON, WT, CW, MC, SC, and DN alternatives. It is interesting to note that WC and DN have the same rank in both partial and complete ranking methods. However, the incomparability information is lost in the complete ranking method which may affect decision-makers ability to make informed decision.

The results of the probabilistic complete ranking showed that the WC alternative obtains the first rank with a probability of 100%. The chances of the SB alternative ranking second and third are 70% and 30%, respectively, whereas the chances of the EOF alternative ranking second and third are 30% and 70%, respectively. The probability of the EON alternative obtaining fourth and fifth ranks is 67% and 33%, respectively, whereas the WT alternative has a probability of 33% and 67% of obtaining the fourth and fifth ranks, respectively. The chance of the CW alternative ranking sixth and seventh is 97% and 3%, respectively, whereas the MC alternative ranks similar to the CW alternative with the values of probability reversed. The SC and DN alternatives rank eighth and ninth with a probability of 100%. It is interesting to note that this method clearly showed the degree of conflict in relative ranking that led to incomparability in the de-

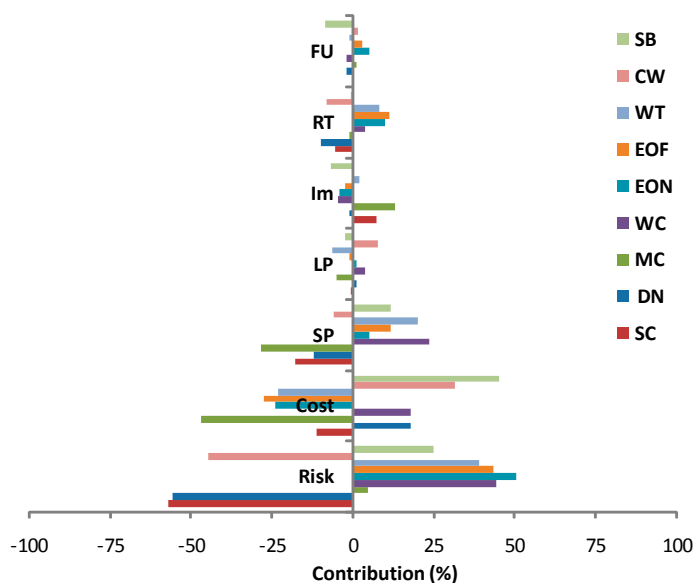


Fig. 2 Contribution (%) of criteria on ranking of alternatives.

terministic partial ranking which is presented above.

The contribution (in percent) of the criteria on ranking the alternatives is shown in Fig. 2. For instance, the three most sensitive criteria that impact the WC alternative are Risk, SP and Cost. Although SP has the least weight among the criteria, its effect is greater than the Cost criterion which is the second most highly weighted criterion. It is worth noting that the ranking of each alternative could be sensitive to different criteria as is seen in this figure. For instance, the SB alternative is sensitive to Cost followed by Risk, SP, FU, IM, and RT criteria, and the CW alternative is sensitive to Risk followed by Cost, RT, LP, SP, FU and IM criteria.

Conclusions

In this paper, the existing framework used for selecting remediation alternatives at mine sites was investigated and improved. The major improvement of the framework includes an introduction of the deterministic and probabilistic multicriteria decision analysis (MCDA) methods. The improved framework was demonstrated using a case study at a mine site.

The results of the deterministic PROMETHEE I analysis showed and ranked the comparable alternatives, and showed the in-

comparable alternatives. The deterministic PROMETHEE II results only showed rankings of the alternatives without incomparability information. In both methods, the uncertainty in the ranking of the alternatives due to input information variation was not shown to decision-makers. On the other hand, the probabilistic PROMETHEE II results showed the probability level at which an alternative could yield certain rankings.

The sensitivity analysis showed the impact of the criteria on ranking the alternatives. Based on the contribution of the criteria, decision makers will be able to leave insensitive criteria for further analysis in order to reduce the complexity of decision making. Meanwhile, they can collect more information on the most sensitive criteria in order to reduce the uncertainty associated with the criteria. The study also showed that the assigned weight of criteria has little effect on ranking the alternatives. However, a limitation of the improved framework is that it addresses the uncertainty associated with the weight of the criteria only. In its present form, this improved framework could be used by decision-makers to select remediation alternatives for mine sites and to select alternatives for mine closures.

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