A PRIORITIZATION METHOD USING HIERARCHICAL NETWORK MODEL FOR MULTI-CRITERIA EVALUATION OF REMEDIAL COUNTERMEASURES

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This paper proposes a prioritization method using hierarchical network model to capture the complexity in the multi-criteria evaluation of remedial countermeasures. Such complexity arises from the complex interdependencies in the decision structure, as well as, from the inherent subjectivity of the decision maker. The proposed method which was built from the Analytic Network Process (ANP) uses the eigenvector approach to derive the local relative priorities and the overall relative priorities from the pairwise comparison matrix and supermatrix, respectively. The processes involved are illustrated using a decision problem drawn from real-life case study of a contaminated site caused by uncontrolled landfill in Japan.

Key Words :multi-criteria evaluation, remedial countermeasures, hierarchical network, Analytic Network Process (ANP), uncontrolled landfill

1. INTRODUCTION

Multiple criteria decision analysis (MCDA) tools have been recognized to play a vital and challenging role in contaminated sites management¹⁾. For instance, prioritization of remedial countermeasures of a contaminated site is a decision making process most often characterized by complexity, uncertainty, and multiple stakeholders with conflicting preferences. Several alternatives have to be considered and evaluated in terms of multiple non-commensurate criteria. There may also be situations where subjective judgments of stakeholders constitute an important part of the

decision process^{2),3)}. The MCDA methods can therefore be used to support such complex planning and decision process by providing a systematic framework for collecting, storing, and processing all relevant information in a manner consistent with the values of the decision maker. However, formal applications of MCDA in the management of contaminated sites are rare at present as compared with its numerous applications in other related areas⁴⁾.

In formal applications of MCDA methods, the decision model is the core of the process which provides the formal specification of how the decision problem is structured and how the different kinds of

information are combined together⁵⁾. To date, one of the most widely used MCDA tool is the Analytic Hierarchy Process (AHP) which decomposes the problem in a hierarchical structure and derives the ratio-scale priorities⁶⁾. AHP's popularity stems from its simplicity, flexibility, intuitive appeal, as well as, its ability to mix quantitative and qualitative criteria in the same decision framework⁷⁾. The AHP has proven its effectiveness as a decision analytic model and have been used to wide spectrum of applications⁸⁾. Furthermore, AHP has been cited as one of the principal MCDA methods currently in use for contaminated sites management and other related areas like natural resource planning²⁾.

Within the context of sustainability, the conceptual planning and design of remedial countermeasures would not only address the technical but also the social dimension of the problem at hand. This increases the problem complexity involved in the evaluation and selection of the most appropriate remedial countermeasure because of the inherent subjectivity of the decision maker, as well as, the complex interdependencies among decision factors. Since the AHP model strictly assumes a linear hierarchy and the mutual independence of elements in each level, the AHP could not capture the real-life interrelationships in a multi-criteria evaluation of countermeasure strategies. Thus, the supermatrix approach, which became popularly known as the

Analytic Network Process (ANP), has become an attractive tool for understanding more of such complex decision problem since it overcomes the limitation of the AHP's linear hierarchic structures^{9),10)}.

Although numerous real-life applications of ANP have been found in the literature, few have been reported in the field of contaminated sites and waste management problem¹¹⁾. Promentilla et al introduced a simplified three-level hierarchical network decision model to describe how interdependence among elements within each level and feedback dependence can be captured in a hierarchic structure, as being applied for the multi-criteria evaluation of remedial countermeasures¹²⁾.

In this paper, we developed a more complex hierarchical network decision structure and proposed the eigenvector approach to derive both the local and overall priorities from the AHP pairwise comparison matrix and ANP supermatrix, respectively. The aim of this paper is to demonstrate the practicability of the proposed method including a sensitivity analysis to clarify the evaluation process in the selection of the most appropriate countermeasure. In the next section, a brief background of ANP supermatrix and the hierarchical network decision model, followed by the algorithm and steps of the proposed method are presented. In section three, the respective procedures involved are illustrated using an example of a decision problem drawn from real-life case study of contaminated site in Japan. In section four, interpretation of the results is further discussed, and followed by the sensitivity analysis before concluding this paper.

2. BACKGROUND OF METHODOLOGY

(1) The Analytic Network Process (ANP)

The ANP is a generalization of Saaty's Analytical Hierarchy Process (AHP) to handle decision problem modeled as 'systems with dependence and feedback'^{6),13),14)}. Such systems can be represented by a directed network (or digraph) in which an arc shows the outer dependence between components or clusters of the system, as well as, loop at a component in case of inner dependence.

Consider a system which has been decomposed into m clusters $C_1, C_2, \dots, C_m$ and let the elements in C_k having n_k elements be denoted as $e_{k1}, e_{k2}, \dots, e_{kn_k}$.

Then, a supermatrix representation of this system (see **Fig.1a**) can be viewed as a partitioned matrix that describes the interaction between the elements and clusters of a system. In this so-called supermatrix, the block matrix contains column of

$$S = \begin{matrix} & \begin{matrix} C_1 & C_2 & \dots & C_m \end{matrix} \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_m \end{matrix} & \begin{bmatrix} \begin{matrix} e_{11} & e_{12} & \dots & e_{1n_1} \\ e_{21} & e_{22} & \dots & e_{2n_2} \\ \vdots & \vdots & \ddots & \vdots \\ e_{m1} & e_{m2} & \dots & e_{mn_m} \end{matrix} & \begin{bmatrix} S_{11} & S_{12} & \dots & S_{1m} \\ S_{21} & S_{22} & \dots & S_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ S_{m1} & S_{m2} & \dots & S_{mm} \end{bmatrix} \end{bmatrix}$$

a) the supermatrix of a network

$$S_{ij} = \begin{bmatrix} w_{i_1(j_1)} & w_{i_1(j_2)} & \dots & w_{i_1(j_{n_j})} \\ w_{i_2(j_1)} & w_{i_2(j_2)} & \dots & w_{i_2(j_{n_j})} \\ \vdots & \vdots & \ddots & \vdots \\ w_{i_{n_i}(j_1)} & w_{i_{n_i}(j_2)} & \dots & w_{i_{n_i}(j_{n_j})} \end{bmatrix}$$

b) the block matrix component of the supermatrix

Fig.1 A generalized supermatrix and an example of block matrix of the supermatrix.

priority weights which represent the impact of all elements in the i th cluster on each of the elements in the j th cluster (see Fig.1b). Some of its entries may be zero corresponding to those elements that have no influence. Saaty⁶⁾ introduced this supermatrix concept to serve as a unifying framework for measurements of ratio scale priority in the ‘decision systems’ wherein hierarchy is a special case.

(2) Hierarchical network decision model

Consider an evaluation problem which can be decomposed into clusters within a multi-level hierarchical network decision structure. Fig.2a is an example of a digraph representation of the four interacting clusters in a three-level hierarchical network. The directions of the arc (or arrow) and loop signify dependence such that the arc and loop pointing into a cluster indicate that its elements influence the elements in the cluster from which the arc is emanating. The structural model incorporates the following types of dependence in a multi-level hierarchy:

- Hierarchic functional dependence as described by the downward arc from the upper-level to the lower-level clusters
- Feedback dependence as described by the upward arc from the lower-level to the upper-level cluster
- Inner-dependence or self-feedback as indicated by loop at each cluster
- Interdependence among clusters in a level as indicated by (horizontal) arc between clusters belonging to the same level
- Feedback control loop as indicated by the arc pointing to the goal cluster.

It should be noted that the feedback control loop can be viewed as a structural dependence indicating that all the elements defined in the hierarchic structure are relevant and influenced by the goal element. Thus, a hierarchical network containing the feedback control loop is a strongly connected digraph structure in which the goal element serves as an overall controlling element that drives the distribution of priorities or dominance weights of each element in the system.

The input to the initial supermatrix of a hierarchical network would depend on the presence and type of dependence described in the digraph (see Fig.2b). A null block matrix (e.g. $S_{41} = 0$) would therefore indicate the absence of direct dependence of the respective cluster from the other cluster. The feedback control loop is represented by a block matrix of unit row vector ($e^T = [1, \dots, 1]$). On the other

a) 3-level hierarchical network with four clusters.

$$S = \begin{bmatrix} 1 & e^T & e^T & e^T \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ 0 & S_{42} & S_{43} & S_{44} \end{bmatrix}$$

b) generalized initial supermatrix.

Fig.2 An example of the digraph structure and supermatrix of a hierarchical network.

hand, the direct dependence between the respective clusters is represented by a block matrix (S_{ij}) whose columns are eigenvectors or local priority vectors derived from an AHP pairwise comparison matrix. Furthermore, a self-feedback loop would be represented by the principal diagonal block matrices (S_{ii} for all $i=j$) containing the priority weights of the interacting elements in the cluster. A special case of this self-feedback is the assumption of mutual independence of elements in the cluster such that each element depends only to itself. This is represented by an identity block matrix (I) on the principal diagonal.

After populating the supermatrix with the respective local priorities, the convergence of this supermatrix when raised to large powers provides a meaningful way to synthesize the local priorities. It was suggested that computing the limit supermatrix to yield the stable overall relative priorities would depend on the stochasticity, irreducibility, primitivity and cyclicity of the supermatrix before raising it to large powers⁹⁾. However, we relax the assumption of stochasticity in the derivation of the meaningful overall priorities of the elements associated with the supermatrix of a hierarchical network structure. Instead, an eigenvector method based on a standardized irreducible evaluation matrix was used to measure the overall priorities or dominance weights. Note that the proposed algorithm would still

allow the cluster weighting as suggested by Saaty^{13),14)} if such weighting makes sense in the decision structure. But the algorithm does not force column stochasticity, i.e., the column normalization of the initial or the cluster-weighted supermatrix to make the matrix's column sum equal to 1, before raising the supermatrix to large powers.

Sekitani and Takahashi¹⁵⁾ suggested that the eigenvector method could be the key to the unified approach of AHP, ANP and their variants. For an irreducible matrix, it was shown that the standardized evaluation matrix, i.e., having the principal eigenvalue equals to unity, could provide the desired evaluation weights by computing the principal eigenvector of the said matrix. Since the digraph representation of the hierarchical network is a strongly connected digraph and its supermatrix (S) representation is an irreducible primitive matrix, the limit supermatrix L exists when the initial supermatrix is standardized by its principal eigenvalue as shown by the following equation:

$$\lim_{p \rightarrow \infty} \left(S / \lambda_{\max} \right)^p = \lim_{p \rightarrow \infty} (\bar{S})^p = L \quad (1)$$

Every column of this limit matrix is a unique positive column eigenvector associated with the principal eigenvalue $\lambda_{\max}$ (see Nikaido¹⁶⁾ for the mathematical proof). This principal column eigenvector corresponds to the stable priorities from the limit supermatrix and can be used to measure the overall relative dominance of one element over another in a hierarchical network structure.

Computationally-wise, we can determine the principal column eigenvector by using the power method developed for a primitive matrix (see Saaty⁶⁾ for the mathematical proof):

$$\lim_{p \rightarrow \infty} \frac{S^p e}{e^T S^p e} = c w \quad (2)$$

where c is a constant and w is the eigenvector corresponding to the principal eigenvalue. The principal eigenvector can therefore be easily obtained in a spreadsheet (e.g. Microsoft Excel 2003) by computing the limiting value of the normalized row sum of a supermatrix raised to large powers. Note that this power method was also used to compute the normalized eigenvector from a positive reciprocal pairwise comparison matrix.

In a graph theoretic sense of the supermatrix as a path matrix, raising the supermatrix to powers enable us to measure the relative dominance of one element over another over a path whose length is equal to that

power of the matrix. Thus, the overall dominance can be captured by considering all the transitivity of different length as indicated in the corresponding powers of the supermatrix. The normalized row sum of such matrix provides the vector of relative dominance over other elements in the subsystem (cluster) as affected by the system's dynamic interaction. For example, the normalized row sum of S^2 provides an index of relative dominance of each element in the system by considering all paths whose length is two. Thus, an element's level of dominance is enhanced or reduced depending on its interdependence with other elements in the digraph structure. The limiting value of the row sum of S^p , the p th power of S may be interpreted to describe the net effect of dominance among elements. This intuitive concept of dominance is analogous to the graph theoretic interpretation of priority weights derived from the principal right eigenvector of a pairwise comparison matrix proposed by Saaty⁶⁾. Thus, the principal column eigenvector of the hierarchical network supermatrix could also provide the ratio-scale priority vector of dominance of the elements as all direct and indirect interactions are captured in the process of convergence when the supermatrix is raised to large powers.

The prioritization method based on hierarchical network has some additional advantages as compared to the standard ANP. First, the feedback control loop introduced in the decision structure ensures a strongly connected ANP model and thus prevents the occurrence of 'nonresponse phenomenon'. This phenomenon as pointed out by Nakagawa and Sekitani¹⁷⁾ refers to the behavior of certain ANP models wherein the final results do not response or invariant to the essential part of the input data. Such shortcoming is addressed by incorporating feedback control loop making the supermatrix irreducible. Second, stochasticity and cluster weighting is not necessary to derive the meaningful final priorities from the supermatrix. Thus, there is no need to conduct value judgment elicitation for cluster weighting wherein certain questions are sometimes difficult to answer as they are counterintuitive or do not make sense at all.

(3) Outline of the proposed method

In general, the proposed prioritization method can be described in the following steps:

- Step 1: Decomposition of the problem into a hierarchical network decision model. The decision model is usually finalized after a considerable amount of discussions among decision makers and stakeholders. Such discussion could provide valuable inputs in the decision making process because structuring the problem helps the decision makers see the 'whole picture' and the issues involved in a complex decision.
- Step 2: Measurement of the local priorities based from the AHP eigenvector method. Local relative priorities were derived from the normalized principal right eigenvector of a pairwise comparison matrix. This matrix contains entries which reflect the value judgment elicited from decision makers or stakeholders in a pairwise comparison process. This approach therefore enables the decision-maker to incorporate experience and knowledge intuitively and express his judgment between every two elements either verbally or quantitatively. The AHP eigenvector method also provides a measure for judgment inconsistency by computing the consistency ratio (CR). The recommended value of CR is less than 0.10 to allow judgment inconsistency in the pairwise comparisons; otherwise, re-evaluation of the pairwise comparative judgment matrix is suggested. For details of

AHP eigenvector method and the calculation of consistency ratio, see Saaty⁶⁾.

- Step 3: Supermatrix synthetic evaluation of the hierarchical network. The supermatrix is initially populated with the respective local priorities. The principal column eigenvector of the said supermatrix is then computed using the power method.
- Step 4: Calculation of the overall relative priorities based from the principal column eigenvector of the hierarchical network supermatrix. The overall relative priorities were normalized according to clusters and levels. These normalized ratio-scale overall priorities can be presented either in distributive or ideal mode. A distributed priority or weight is normalized by the total priority or weight in the cluster or level while an idealized weight is normalized by the largest weight in the cluster or level.

To elucidate more the process of evaluation using the proposed method, a numerical example is presented in the next section.

3. AN ILLUSTRATIVE EXAMPLE: A CASE STUDY OF UNCONTROLLED LANDFILL

(1) Problem description

The hypothetical problem is based on a real case

Fig.3 The contaminated sites caused by uncontrolled landfill.

Table 1 Definition of countermeasure strategies used in this case study.

Remedial Alternatives	Site remediation containing the waste layer	Prevention of contaminant spreading	Remediation of Surrounding Area
Alternative 1 (A1)	Removal of all waste materials and off-site treatment (e.g., incineration, vitrification) and disposal of the treated waste.		In-situ remediation (e.g., enhanced bioremediation, natural attenuation)
Alternative 2 (A2)	In-situ remediation (e.g., enhanced bioremediation, soil washing, etc.)	Capping and hydraulic control (groundwater extraction)	In-situ remediation (e.g., enhanced bioremediation, natural attenuation)
Alternative 3 (A3)	In-situ remediation (e.g., enhanced bioremediation, soil washing, etc.)	Capping, vertical cut-off wall (sheet piling, chemical grout, etc.)	In-situ remediation (e.g., enhanced bioremediation, natural attenuation)

study of a contaminated site in Japan. In 1996, wastes such as industrial waste oils and waste solvents that should be disposed in a controlled landfill were illegally disposed to a privately-owned inert-type landfill in one of the Japan's Honshu prefectures. Note that the inert-type landfill is considered as the least controlled landfill, i.e., without any liner or leachate treatment facility, according to Japan's legal classification of landfill¹⁸⁾. The uncontrolled landfill site encompasses an area of 2800 m² and estimated to contain about 40,000 m³ of waste materials¹⁹⁾. Field investigations revealed that the site and the surrounding area were contaminated with hazardous substances which are well above the Japan's regulatory standard set for groundwater (see Fig.3).

However, the owner of this uncontrolled landfill did not have the financial resources to undertake the clean-up of the contaminated site. In such case, the law requires that the prefectural government (in which the site is located) will be responsible for the remediation of the site. Hence, the main decision maker is the prefectural government authority who will lead in the planning, design and implementation of the remediation project at the site.

With these considerations, three countermeasure strategies were identified (see Table 1). In making a strategic selection of the countermeasure to be developed for detailed design and analysis, the following remediation objectives were defined as follows: 1) to be cost-effective in protecting human

Fig. 4 Evaluation criteria and attributes used in this case study.

Fig. 5 An example of interdependence among attributes used in this case study.

health and the environment during and after the remediation project; 2) to be technically feasible in meeting the effluent standard and environmental standard at the landfill site and the surrounding area, respectively; 3) to minimize future contaminant releases from the site and the off-site migration to surface water and groundwater; and 4) to be acceptable to all concerned stakeholders. In this decision environment, the major stakeholders who were considered are as follows: 1) the local community of the city where the contaminated site is located and 2) the general public of the said prefecture.

There are numerous decision factors that could influence the decision makers and stakeholders on the choice of the most appropriate remedial alternative for the site. In this study, four primary evaluation criteria were defined based on the concept of sustainability. These criteria are environmental effectiveness (EE), implementability (IM), financial affordability (FA) and social acceptability (SA). The performance measures or attributes of each evaluation criterion were then identified to assess the relative desirability of the remedial alternatives. Fig. 4 is an example of the attributes which were obtained from a group discussion for this case study. Table 2 gives a brief description of these evaluation criteria and attributes. Furthermore, Fig. 5 depicts an example of the interdependence among the attributes which were identified from the said group discussion. For example, the local community acceptance (LC) is perceived to be influenced by the associated residual risk (RR) of an alternative. This relationship is described in the structural model (or digraph) by defining an arc emanating from the LC and pointing

a) hierarchical network decision structure used in the case study.

$$S = \begin{array}{c|cccccc} & 1 & e^T & e^T & e^T & e^T & e^T \\ \hline S_{21} & I & 0 & 0 & 0 & 0 & 0 \\ 0 & S_{32} & I & S_{34} & 0 & S_{36} & S_{37} \\ 0 & S_{42} & S_{43} & I & 0 & S_{46} & S_{47} \\ 0 & S_{52} & 0 & S_{54} & I & S_{56} & S_{57} \\ 0 & S_{62} & 0 & 0 & 0 & S_{66} & S_{67} \\ 0 & 0 & S_{73} & S_{74} & S_{75} & S_{76} & I \end{array}$$

b) supermatrix representation.

where :

$e^T = [1, \dots, 1]$

0 = null block matrix

I = identity block matrix

S_{ij} = nonnegative block matrix

Fig. 6 The decision structure used in this case study and its supermatrix representation.

to the RR node (see Fig. 5).

(2) Decision structure under consideration

Fig. 6a describes the hierarchical network model as described in a digraph to represent the decision problem. The uppermost level which will be referred to as the goal level contains the goal cluster and its single goal element. This goal element represents the nature of the decision problem, i.e., prioritization of remedial alternatives which focus on the selection of the most appropriate countermeasure for the case site. The second level which will be referred to as the

Table 2 Definition of evaluation criteria and attributes used in this case study.

Criteria	Attributes	Description ^a
1. Environmental Effectiveness (EE)	This evaluation criterion refers to the effectiveness of the remedial option to protect human health and the environment	
	Residual risk (RR)	The potential remaining risk may be expressed quantitatively, such as by cancer risk levels, or hazard index for non-carcinogenic effects, or by the volume or concentration of contaminant
	Adequacy and reliability of control (AR)	This refers to the adequacy of control in terms of managing risk from treatment residuals or wastes that remain at the site and the long-term reliability of control to prevent the spreading of contamination
	Impact on worker during remediation (IW)	This factor assesses threats that may be posed to workers, as well as, the effectiveness and reliability of protective measures for workers that could be taken during the remediation activities
	Impact on local community during remediation (IC)	This factor addresses any (risk) impact on the local community that is directly affected by the implementation of the proposed remedial action, such as dust from excavation or air-quality impacts from the operation of an incinerator, traffic during transportation, etc
2. Implementability (IM)	This evaluation criterion refers to the technical and administrative feasibility of implementing an alternative	
	Administrative implementability (AI)	This refers to activities needed to coordinate with other offices and agencies (e.g. obtaining permits for off-site activities or rights-of-way for construction). This may also include the availability of various services and materials required during its implementation
	Technical feasibility (TF)	This relates to the technical difficulties and unknowns associated with a technology employed by an alternative. This also includes the reliability of the technology to meet the performance goal during construction and operation
	Maturity of Technology (MT)	This refers to the pertinent track record in the local or international setting or proven performance of the technology employed by an alternative
3. Financial affordability (FA)	This evaluation criterion refers to the financial cost associated with an alternative	
	Capital Cost (CC)	Capital costs consist of direct (construction) and indirect (non-construction and overhead) costs. Direct costs include expenditures for the equipment, labor and materials necessary to install remedial actions. Indirect costs include expenditures for engineering and other services that are not part of actual installation activities but are required to complete the installation of remedial alternatives
	Operation and Maintenance Cost (OM)	This refers to annual costs are post-construction costs necessary to ensure the continued effectiveness of a remedial action such as operating labor costs, maintenance material costs, replacements cost and the like
4. Social acceptability (SA)	This refers to the stakeholders concern with regard to the acceptability of an alternative from a socio-psychological, socio-economic, socio-political or socio-cultural context	
	Local community acceptance (LC)	This factor addresses not only the concerns of the people living near the site, but also the other residents of city where the site is located including the municipal government
	General public acceptance (GP)	This factor addresses the concerns of the general public of the Prefecture who indirectly bear the cost of remediation in the form of taxes

^a Some of the descriptions were adapted from USEPA²⁰⁾

Table 3 Description of type of dependence associated with the arc and the corresponding input to respective block matrix.

Arc/Loop ^a	Dependence	Block matrix ^b	Input
2-1	Hierarchic functional dependence	S_{21}	Relative dominance (local priorities) of criteria with respect to goal
3-2, 4-2, 5-2, 6-2	Hierarchic functional dependence	$S_{32}, S_{42}, S_{52}, S_{62}$	Relative dominance (local priorities) of attributes with respect to their parent criteria
7-3, 7-4, 7-5, 7-6	Hierarchic functional dependence	$S_{73}, S_{74}, S_{75}, S_{76}$	Relative dominance (local priorities) of alternatives with respect to each attribute
1-1, 2-2, 3-3, 4-4, 5-5, 6-6, 7-7	Self feedback / inner dependence	$S_{11}, S_{22}, S_{33}, S_{44}, S_{55}, S_{66}, S_{77}$	Relative influence (local priorities) of elements with respect to each element belonging to the same cluster. If mutual independence of elements is assumed, the corresponding block matrix is an identity matrix (I).
4-3, 3-4, 5-4, 3-6, 4-6, 5-6	Interdependence among attribute clusters in a level	$S_{43}, S_{34}, S_{54}, S_{36}, S_{46}, S_{56}$	Relative influence (local priorities) of elements in a cluster with respect to an element belonging to another cluster but in the same level
3-7, 4-7, 5-7, 6-7	Feedback dependence	$S_{37}, S_{47}, S_{57}, S_{67}$	Relative dominance (local priorities) of attributes with respect to each alternative
1-2, 1-3, 1-4, 1-5, 1-6, 1-7	Feedback control loop	$S_{12}, S_{13}, S_{14}, S_{15}, S_{16}, S_{17}$	Goal act as the overall controlling element in a strongly connected decision structure. The corresponding block matrix is a row vector of 1 ($e^T = [1, \dots, 1]$)

^aNotation of arc i-j means the arc points to cluster i from cluster j. ^bBlock matrix of the supermatrix in **Fig.6**.

evaluation criteria level contains the evaluation criteria cluster and its four elements. The third level which will be referred to as the attributes level contains the four clusters and their elements associated with the respective evaluation criteria. The lowest level which will be referred to as the alternatives level contains the alternatives cluster and its three elements.

As shown in **Fig.6b**, the supermatrix representation of the hierarchical network consists of block matrices associated with the different types of dependence indicated by the arcs (or arrows) and loops in the digraph. **Table 3** describes the input to these block matrices and the type of dependence each arc represents.

(3) Pairwise comparisons to measure local priorities

This is accomplished by asking the decision maker to assess the relative dominance of each set of child elements (or nodes to which the arc is pointing), in a pairwise fashion with respect to the common parent element (or the common node from which the respective arcs are emanating). **Table 4** provides the verbal judgment scale for comparisons and its equivalent numerical intensity which will be used as entry in the pairwise comparison matrix. Saaty^(6),14) derived this scale from the basic mathematics of neural firing that leads to the well-known logarithmic law of stimulus response. In addition, this scale has also been validated for effectiveness in many

applications. Note that the term ‘dominance’ can be interpreted as the greater influence with respect to a certain property. To say that one element dominates another is a generic way of saying that it is greater or more important, more preferred, or more likely to occur than the other element¹²⁾. For the purpose of brevity, selected samples of pairwise comparative judgment matrix (PCJM), as well as, the typical questions for value elicitation were presented.

The entry to the pairwise comparison matrices was made after a series of discussions among the selected members of the Laboratory of Sound Material Cycle Systems Planning at Hokkaido University. These said individuals have background knowledge and experience concerning the problem at hand. The consensual verbal judgments were then obtained after the deliberations of available information relevant to the site.

Table 4 Nine-point scale for pairwise comparison.

Intensity	Verbal scale of dominance
1	Equal dominance
3	Moderate dominance
5	Strong dominance
7	Very strong dominance
9	Absolute or extreme dominance
2,4,6 and 8	For compromise between the above values
Reciprocal	Reciprocals for inverse comparison

Table 5 Pairwise comparison matrix for environmental effectiveness attributes with respect to EE.

EE	RR	AR	IW	IC	e-vector
RR	1	1	3	3	0.3750
AR	1	1	3	3	0.3750
IW	1/3	1/3	1	3	0.1250
IC	1/3	1/3	1/3	1	0.1250

CR= 0.0000

Table 6 Pairwise comparison matrix for alternatives with respect to RR.

RR	A1	A2	A3	e-vector
A1	1	5	3	0.6370
A2	1/5	1	1/3	0.1047
A3	1/3	3	1	0.2583

CR= 0.0370

The objectivity and reliability of the process of priority derivation would depend on the interpretation of the said information as perceived by the involved individuals. It is not the scope of this paper to prescribe and validate the results from a normative perspective but to make explicit the preference value using a descriptive decision model. This follows from the AHP/ANP axiomatic foundation that thoughtful individuals who have reasons for their beliefs should make sure that their ideas are adequately represented in the decision model¹⁴⁾. In such situation, it is also essential to be sensitive to the existence of some inherent limitations on objectivity since the information is most often imprecise, uncertain or ill-defined. Rather than trying to dismiss or disregard the subjectivity which results from these limitations of objectivity, the approach is to objectively process it. In other words, the priorities or weights derived from the pairwise comparison matrix in this paper reflect the value judgments that are subjective evidence specific to the problem under study. Sensitivity analysis were then conducted by varying the weights of the evaluation criteria as discussed in section four to provide insights on the solution robustness of the method.

a) Pairwise comparison for hierarchic functional dependence

In a top-down approach commonly used in AHP, the relative importance of criteria with respect to the goal is first determined. The relative importance of attributes with respect to their parent criteria is then computed. Finally, evaluation of the alternatives with respect to these attributes is done by obtaining the relative preference or relative impact of alternatives with respect to each attribute.

In this numerical example, it is assumed first that

Table 7 Pairwise comparison matrix for financial affordability attributes with respect to AI.

AI	CC	OM	e-vector
CC	1	2	0.6667
OM	1/2	1	0.3333

CR = 0.0000

Table 8 Pairwise comparison matrix for social acceptability attributes with respect to A1.

A1	LC	GP	e-vector
LC	1	3	0.7500
GP	1/3	1	0.2500

CR = 0.0000

the primary evaluation criterion have equal importance or impact on the prioritization of remedial alternatives. Thus, the distributed priority weight of each criterion is 0.250. This is represented by $S_{21} = [0.250, 0.250, 0.250, 0.250]^T$ in the supermatrix (see **Fig.7**). On the other hand, the relative importance weights of attributes were distributed according to the perceived dominance of one attribute over another with respect to the satisfaction of the parent criteria.

For example, in **Table 5**, the normalized eigenvector (e-vector) from the pairwise comparison judgment matrix provides the relative importance weights of the environmental effectiveness attributes. For value judgment elicitation, a typical question can be formulated as this “Comparing residual risk (RR) and impact on the local community (IL), which one is more important with respect to environmental effectiveness (EE), and by how much is it greater?” If the decision maker feels that RR is moderately more important than IL, then a numerical rating of 3 is entered to the intersection of the row of RR and column of IL as indicated in **Table 5**.

Likewise, a set of pairwise comparisons is made to determine the relative preference weights of alternatives with respect to each attribute. **Table 6** shows one example of PCJM that was used to compute the e-vector and measure the distributed preference weights of alternatives with respect to RR. For value judgment elicitation, a typical question can be formulated as this “Comparing A1 and A2, which one is more preferred with respect to residual risk (RR), and by how much is it greater?”

b) Pairwise comparison for interdependence among attributes

After defining the structure of interdependent relationships among attributes (see **Fig.5**), pairwise comparisons were done to consider the interdependencies among attributes. One such comparison is presented in **Table 7**. It represents the

result for the relative impact weights of the elements in the financial affordability cluster with respect to AI as the control or parent attribute. The question asked to the decision maker in evaluating the relative influences can be formulated as this “When considering AI with regards to its impact on the implementability of an appropriate countermeasure and comparing CC and OM, which one influences AI more and by how much is it greater?”

c) Pairwise comparison for feedback dependence

In a bottom-up approach, feedback dependence of attributes cluster from alternatives could have significant effect on assessing the relative importance or dominance of an attribute when the set of alternatives under evaluation is considered. For example, **Table 8** describes the relative dominance weights of elements in the social acceptability cluster with respect to each alternative. The question for value elicitation can be formulated like this “When considering A1 as an appropriate countermeasure and comparing LC and GP, which one dominates or contributes more in the attainment of social acceptability and by how much is it greater?”

(4) Supermatrix synthetic evaluation and calculation of the overall priorities

Fig.7 depicts an example of the supermatrix containing the block matrices that were populated by local priorities such as those eigenvectors derived in section three. Then, the principal column eigenvector was computed for this supermatrix as shown in **Table 9**. The final weights or the overall relative priorities are computed from the normalized eigenvector according to clusters and levels for both distributive

and ideal mode (**Table 9**). For example, the distributed priority of CC in the financial affordability cluster is computed as follows:

$$0.5954 = 0.0566 / (0.0566 + 0.0385)$$

Likewise, the idealized priority of CC in the attributes level is computed as follows:

$$0.7513 = 0.0566 / 0.0791$$

where 0.0791 is the priority vector of MT, which has the largest weight in the attributes level.

4. DISCUSSION

In **Table 9**, the principal column eigenvectors and the overall relative priorities are summarized for the hierarchical network decision model (HN model) used in this numerical example. It is observed from the idealized priorities of the alternatives cluster (or level) that A3 (1.0000) is the most preferred countermeasure strategy but it is followed closely by A1 (0.9788). Note that the overall relative weights of the elements in the criteria cluster (or level) indicates the same initial equal weighting of EE, IM, FA and SA. Such result is expected from this model since the interdependence among criteria and feedback dependence from the lower-level clusters was not considered. On the other hand, the relative priorities of the attributes were adjusted from their initial (local) weights to the final overall weights when interdependence among attributes and its feedback dependence from the alternatives were captured in the structure.

S	G	EE	IM	FA	SA	RR	AC	IW	IL	AI	TF	MT	CC	OM	LC	GP	A1	A2	A3
G	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
EE	0.250	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IM	0.250	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FA	0.250	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SA	0.250	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RR	0	0.375	0	0	0	1	0	0	0	0	0	0	0	0	0.429	0.429	0.417	0.063	0.083
AC	0	0.375	0	0	0	0	1	0	0	0	0	0	0	0	0.429	0.429	0.417	0.063	0.083
IW	0	0.125	0	0	0	0	0	1	0	0.500	0	0	0	0	0	0	0.083	0.438	0.417
IL	0	0.125	0	0	0	0	0	0	1	0.500	0	0	0	0	0.143	0.143	0.083	0.438	0.417
AI	0	0	0.444	0	0	0	0	0	0	1	0	0	0	0	0	0	0.105	0.603	0.648
TF	0	0	0.444	0	0	0.250	0.500	0	0	0	1	0	0.250	0.250	0.250	0.250	0.637	0.082	0.230
MT	0	0	0.111	0	0	0.750	0.500	0	0	0	0	1	0.750	0.750	0.750	0.750	0.258	0.315	0.122
CC	0	0	0	0.500	0	0	0	0	0	0.667	0	0	1	0	0	0.500	0.167	0.875	0.857
OM	0	0	0	0.500	0	0	0	0	0	0.333	0	0	0	1	0	0.500	0.833	0.125	0.143
LC	0	0	0	0	0.833	0	0	0	0	0.750	0	0	0	0	1	0.250	0.750	0.500	0.500
GP	0	0	0	0	0.167	0	0	0	0	0.250	0	0	0	0	0	0.750	0.250	0.500	0.500
A1	0	0	0	0	0	0.637	0.570	0.089	0.089	0.091	0.455	0.333	0.109	0.528	0.570	0.500	1	0	0
A2	0	0	0	0	0	0.105	0.097	0.352	0.352	0.455	0.091	0.333	0.582	0.140	0.097	0.250	0	1	0
A3	0	0	0	0	0	0.258	0.333	0.559	0.559	0.455	0.455	0.333	0.309	0.333	0.333	0.250	0	0	1

Fig.7 An example of the supermatrix (HN model) of the hierarchical network.

S	G	EE	IM	FA	SA	RR	AC	IW	IL	AI	TF	MT	CC	OM	LC	GP	A1	A2	A3
G	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
EE	0.250	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IM	0.250	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FA	0.250	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SA	0.250	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RR	0	0.375	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
AC	0	0.375	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
IW	0	0.125	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
IL	0	0.125	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
AI	0	0	0.444	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
TF	0	0	0.444	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
MT	0	0	0.111	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
CC	0	0	0	0.500	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
OM	0	0	0	0.500	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
LC	0	0	0	0	0.833	0	0	0	0	0	0	0	0	0	1	0	0	0	0
GP	0	0	0	0	0.167	0	0	0	0	0	0	0	0	0	0	1	0	0	0
A1	0	0	0	0	0	0.637	0.570	0.089	0.089	0.091	0.455	0.333	0.109	0.528	0.570	0.500	1	0	0
A2	0	0	0	0	0	0.105	0.097	0.352	0.352	0.455	0.091	0.333	0.582	0.140	0.097	0.250	0	1	0
A3	0	0	0	0	0	0.258	0.333	0.559	0.559	0.455	0.455	0.333	0.309	0.333	0.333	0.250	0	0	1

Fig.8 An example of the supermatrix of the AHP* hierarchical network.

Table 9 The principal eigenvector and the overall priorities derived from the hierarchical network (HN model).

Decision structure (HN model)			HN (initial) local wts.	Overall (final) relative priorities				
Level	Cluster	Elements		e-vector	Cluster (dist)	Cluster (ideal)	Level (dist)	Level (ideal)
Goal		G	1.0000	0.2712	1.0000	1.0000	1.0000	1.0000
Criteria		EE	0.2500	0.0252	0.2500	1.0000	0.2500	1.0000
		IM	0.2500	0.0252	0.2500	1.0000	0.2500	1.0000
		FA	0.2500	0.0252	0.2500	1.0000	0.2500	1.0000
		SA	0.2500	0.0252	0.2500	1.0000	0.2500	1.0000
Attributes	EE	RR	0.3750	0.0296	0.2548	0.9634	0.0647	0.3743
		AR	0.3750	0.0296	0.2548	0.9634	0.0647	0.3743
		IW	0.1250	0.0262	0.2258	0.8535	0.0573	0.3316
		IL	0.1250	0.0307	0.2645	1.0000	0.0672	0.3885
	IM	AI	0.4444	0.0320	0.1979	0.4045	0.0699	0.4045
		TF	0.4444	0.0506	0.3128	0.6392	0.1105	0.6392
		MT	0.1111	0.0791	0.4893	1.0000	0.1729	1.0000
	FA	CC	0.5000	0.0566	0.5954	1.0000	0.1237	0.7153
		OM	0.5000	0.0385	0.4046	0.6797	0.0841	0.4862
	SA	LC	0.8333	0.0568	0.6706	1.0000	0.1241	0.7177
		GP	0.1667	0.0279	0.3294	0.4912	0.0610	0.3526
Alternatives		A1	0.0000	0.0617	0.3624	0.9788	0.3624	0.9788
		A2	0.0000	0.0455	0.2674	0.7221	0.2674	0.7221
		A3	0.0000	0.0630	0.3702	1.0000	0.3702	1.0000

For example, although the CC (0.5000) and OM (0.5000) are weighted equally, the overall relative priorities of CC (.6000) became greater than that of OM (0.4000) (see **Table 9**). It is also observed from the idealized overall relative weights that the dominating elements among the 11 attributes are MT (1.0000), LC (.7177), CC (0.7153), TF (0.6392), OM (.4862), and AI (.4045). Note that these results could only be interpreted specific to the constructed

decision structure and the value judgment inputs provided by the decision maker who had some knowledge on the problem context and the local conditions of the case site.

In order to understand more the value of the hierarchical network model in the clarification of the evaluation process, the following scenarios were considered for sensitivity analysis:

- 1) The scenario (AHP* scenario) in which

using the same framework of the HN supermatrix but without considering the interdependence among elements in each level and without considering the feedback dependence from the alternative cluster to the attributes clusters. **Fig.8** illustrates an example of the AHP* supermatrix. This model can be viewed as analogous to the standard AHP model with a strict assumption of mutual independence among elements within the clusters in each level.

- 2) The scenario (S-EE scenario) in which the environmental effectiveness (EE) is strongly more important over the other criteria whose importance are indifferent to each other. Thus, the initial equal weighting of the criteria with respect to the goal was replaced by the following weights obtained from the pairwise comparison matrix ($CR = 0.0000$): $EE = 0.6250$, $IM = FA = SA = 0.1250$.
- 3) The scenario (S-IM scenario) in which the implementability is strongly more important over the other criteria whose importance are indifferent to each other. Thus, the initial equal weighting of the criteria with respect to the goal was replaced by the following weights obtained from the pairwise comparison matrix ($CR = 0.0000$): $IM = 0.6250$, $EE = FA = SA = 0.1250$.
- 4) The scenario (S-FA scenario) in which the financial affordability is strongly more important over the other criteria whose importance are indifferent to each other. Thus, the initial equal weighting of the criteria with respect to the goal was replaced by the following weights obtained from the pairwise comparison matrix ($CR = 0.0000$): $FA = 0.6250$, $EE = IM = SA = 0.1250$.
- 5) The scenario (S-SA) in which the social acceptability is strongly more important over the other criteria whose importance are indifferent to each other. Thus, the initial equal weighting of the criteria with respect to the goal was replaced by the following weights obtained from the pairwise comparison matrix ($CR = 0.0000$): $SA = 0.6250$, $EE = IM = FA = 0.1250$.

In **Table 10** the results of the normalized relative weights derived from the scenario AHP* are compared to that of the standard AHP. It can be observed that the local relative priorities of AHP correspond with the initial relative weights and the overall relative weights derived from cluster-wise normalization of the eigenvector of AHP*

supermatrix. Furthermore, the AHP global priorities of elements with respect to goal were shown to be equivalent to the overall relative weights derived from level-wise normalization of the said eigenvector. This supports the proposition that an AHP model is a special case of the hierarchical network decision model.

Although a more comprehensive sensitivity analysis can also be carried out, the simplified analysis used in this paper would be sufficed for the purpose of illustration. **Fig.9** and **Fig.10** depicts the sensitivity of the overall relative priorities (derived from level-wise normalization of the eigenvector) of the attributes and alternatives, respectively. The results show how the relative dominance of the attributes behaves at different scenarios and in effect, influences the prioritization of the remedial countermeasures. For example, A1 is preferred more against A3 in the AHP* scenario but when interdependence among attributes and feedback dependence was incorporated, A3 becomes the most preferred in the HN model (see **Fig.10**). This effect can be attributed to the change of the distribution of the overall relative priorities of attributes as complex interdependencies in the decision structure are captured as shown in **Fig.9**.

For example, LC (0.21) has the highest priority weight while MT (0.03) has the lowest priority weight in the AHP* scenario. But in the HN model, MT (0.17) becomes the most dominant attribute followed by LC (0.12). The results imply how sensitive the resulting priorities on the nature of the decision structure.

Moreover, with the incorporation of more complex interdependencies that is not limited to strict hierarchy, the structural model contributes to the robustness of the results as all possible direct and indirect interactions are captured in the evaluation process. For example, MT becomes the most dominant attribute in every scenario of the hierarchical network. Although MT has the lowest priority in the implementability cluster, it obtains the highest overall priority because of its relatively high priority of impact on the other elements in the attributes level. Moreover, some attributes like MT would act as an influential attribute as it is less affected by the rest of the system than it has impact on it as depicted graphically in **Fig. 5**. Thus, the underlying decision structure could lead to a certain phenomena in which an apparently unimportant element in the system becomes important overall.

Table 10 Comparison of priorities between the standard AHP and the AHP* hierarchical network.

Decision structure			std AHP		AHP* model		
Level	Cluster	Elements	local priority	global priority	e-vector	cluster (dist)	Level (dist)
Goal		G	1.0000	1.0000	0.4056	1.0000	1.0000
Criteria		EE	0.2500	0.2500	0.0692	0.2500	0.2500
		IM	0.2500	0.2500	0.0692	0.2500	0.2500
		FA	0.2500	0.2500	0.0692	0.2500	0.2500
		SA	0.2500	0.2500	0.0692	0.2500	0.2500
Attributes		RR	0.3750	0.0938	0.0177	0.3750	0.0938
		AR	0.3750	0.0938	0.0177	0.3750	0.0938
		IW	0.1250	0.0313	0.0059	0.1250	0.0313
		IL	0.1250	0.0313	0.0059	0.1250	0.0313
		AI	0.4444	0.1111	0.0210	0.4444	0.1111
		TF	0.4444	0.1111	0.0210	0.4444	0.1111
		MT	0.1111	0.0278	0.0052	0.1111	0.0278
		CC	0.5000	0.1250	0.0236	0.5000	0.1250
		OM	0.5000	0.1250	0.0236	0.5000	0.1250
		LC	0.8333	0.2083	0.0393	0.8333	0.2083
		GP	0.1667	0.0417	0.0079	0.1667	0.0417
Alternatives		A1	0.4077	0.4077	0.0525	0.4077	0.4077
		A2	0.2317	0.2317	0.0299	0.2317	0.2317
		A3	0.3607	0.3607	0.0465	0.3607	0.3607

Fig. 9 Sensitivity analysis on the overall priorities of attributes.

Fig. 10 Sensitivity analysis on the overall priorities of alternatives.

It is also shown in Fig.9 that the LC, CC and TF are the other dominating attributes aside from MT, whose priorities are more than 0.10 in every scenario. This confirms the perceived importance of certain attributes and also reveals the other attributes which were previously thought to be unimportant but which play a leading role because of the indirect interactions. These attributes would be the influential and key factors in the assessment of the overall desirability of alternatives.

As shown in Fig.10, A3 is ranked first at S-EE, S-IM and S-FA scenarios while A1 is ranked first at S-SA scenario. On the other hand, A2 is ranked last in every scenario. Thus, in a scenario where implementability (S-IM) or financial affordability (S-FA) is prioritized more than the other criteria, A3 is most likely to be preferred more against A1 because of the increased relative dominance of attribute AI and CC. On the other hand, the relative degree of preference of A1 over A3 was increased in a scenario where environmental effectiveness (S-EE) or social acceptability (S-SA) is prioritized more because of the increased relative dominance of RR, AR, LC and GP. However, since the environmental effectiveness (EE) is influenced not only by RR and AR but also by IW and IL, the impact of RR and AR on the prioritization of the alternative is buffered in the S-EE scenario. Note that A1 is perceived to be preferred more than A3 with respect to RR and AR but A3 is preferred more with respect to IW and IL. In effect, the results of S-EE scenario showed A3 as

the overall most preferred alternative but its relative desirability is followed closely by A1. On the other hand, looking at the S-SA scenario in which LC and GP are the attributes of concern, A1 is obviously the most preferred but it is followed closely by A3. This may be explained by A3's satisfactory level of desirability with respect to certain attributes such as IL, TF and MT which also have impact on LC and GP. These results may suggest that A3 is most likely to be selected as an appropriate countermeasure strategy provided that its perceived social acceptability is improved. However, there is a possibility that A1 could also be selected if the decision maker gives too much importance on social acceptability and provided that its perceived implementability is improved. Thus, A1 and A3 can be subjected to further deliberation to ascertain the robustness of the decision from an analytic-deliberative process.

5. SUMMARY AND CONCLUSIONS

In this paper, we proposed a formal multiple criteria decision analysis based on a hierarchical network decision model for the evaluation of contaminated site remedial countermeasures. The proposed prioritization method used the power method to approximate the eigenvector to compute both the local and overall priorities from the AHP pairwise comparison judgment matrix and the ANP

supermatrix, respectively. This method can be easily implemented in a spreadsheet such as the Microsoft Excel 2003. An illustrative example was then presented to elucidate the process, as being applied to a decision problem based on real-life case study of contaminated site caused by an uncontrolled landfill in Japan. A simplified sensitivity analysis was also carried out to show how the decision structure and the trade-off weights of the primary evaluation criteria could influence the prioritization results.

Results from the sensitivity analysis implied that either A1 or A3 could be considered as the most appropriate countermeasure depending on the situation while A2 would seem to be the least preferred countermeasure for the case site. With respect to environmental effectiveness (EE) and social acceptability (SA), A1 is perceived to be the most preferred but A3's overall desirability seems to be satisfactory. With respect to implementability (IM) and financial affordability (FA), A3 outperforms A1. Furthermore, the maturity of technology (MT), local community acceptance (LC), capital cost (CC) and technical feasibility (TF) are identified as the dominating attributes in the decision structure.

It should be noted that the above findings must also be viewed in the light of the characteristic of the decision structure under consideration, as well as, the inputs provided by the decision makers. The prioritization results could be influenced largely by the analytic-deliberation process. Thus, this paper had demonstrated how the method could effectively capture the complexity of decision making process in a systematic manner and aid the decision makers and stakeholders in the deliberation.

First, the systemic view of the evaluation process allows for more complex interdependencies in the hierarchic decision structure, which has been rarely applied in the field of contaminated sites management. However, such feature of the method could be seen by some practitioners as a potential drawback as well. As structural complexity increases by incorporating more clusters and elements and their interdependencies, the number of pairwise comparisons, as well as, time and resources to elicit value judgment would definitely increase. However, the benefit of the method in addressing such complexity and facilitating communication among the decision makers and stakeholders toward a sound decision may outweigh the cost of the lengthy and cumbersome process involved.

Second, the method which uses the mathematical foundation of AHP and ANP provides an analytical framework to structure and process the inherent subjective value judgment of the individual or group of decision makers and stakeholders. The method

would not only lead to the overall priorities of the remedial countermeasures but also enables the decision maker to understand the impact of the decision structure and weighting that reflects his value judgment. On the other hand, the dependence of the outcome of the model on the uncertain input from the decision maker can also be viewed by some practitioners as a practical limitation. For example, a different set of decision makers, applying the method to the same problem, may arrive at a different problem structure and priorities. However, if the clarification of the evaluation process would be considered as the primary purpose of an MCDA tool rather than the numerical values like the priorities or ranking it provides; then, using such explicit and transparent process may help the conflicting parties to reach consensus because disagreements can be specifically identified in a group decision making environment.

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(Received January 12, 2006)