방사선 방어학회지
제19권 제2호 1994

■ 논 문 ■

An Analytical Methodology for Evaluating Radiological Protection Alternatives Using Analytical Hierarchy Process

Sang-duk Sa, Masakuni Narita*

Radiation Safety Division, Ministry of Science and Technology
Hokkaido University*

ABSTRACT

This study aims to introduce a prescriptive methodology to comprehensively support the analysis of decision process by the use of Saaty's Analytical Hierarchy Process for the optimization of radiation protection. The analytical Hierarchy Process for the optimization of radiation protection. The analytical process for the problem of selecting options among given protection alternatives is illustrated with the data of the uranium mine example in *ICRP Publ. 55*. This technique, unlike other conventional selection method, is considered to provide a useful tool for the protection manager with respect to its ease of use and simplification in the choice of optimal alternative associated with radiological protection.

Key words: *Analytical Hierarchy Process, Radiation Protection, Optimization.*

Introduction

This paper considers the problem of evaluating the radiological protection factors specified as relevant in the optimization. The optimization of radiation protection is gradually being recognized as an important principle[1] in implementing the International Commission on Radiological Protection(ICRP) system, but the study of optimization and decision-making techniques is rather scarce compared with the importance of its concept[2].

The choice of appropriate protection options is an important decision because it involves complicated factors such as the occupational doses, the protection cost and the discomfort associated with the work environments which are both quantitative and qualitative. Cost-benefit analysis that evaluates alternatives quantitatively by relating benefits to assosiated costs is the most common technique in the field of radiation protection. This technique has been used in optimization study extensively since the ICRP introduced its concept in the earlier publications[3].

However, although cost-benefit analysis may be a good evaluation technique for the purely quantitative problems which can be illustrated with a single objective function, it fails to consider the relevant factors which are not simple to be transformed into a monetary valuation. Due to such restrictions in the cases of real problems on radiological protection, the ICRP recently introduced the alternative decision-aiding techniques such as multi-attribute utility analysis and multi-criteria outranking analysis together with conventional methods in *ICRP Publ.55*[4]. The alternative techniques may overcome the difficulty to quantify in monetary terms, these methods are considered to have abstract and cumbersome aspects to appropriately determine the utility functions.

The authors have studied the application of the goal programming method that is regarded as an adequate and flexible technique to the optimal allocation problem of radiation workers under multiple conflicting objectives[5]. This paper demonstrates a new application study with an evaluation methodology based on Saaty's Analytical Hierarchy Process(AHP)[6] for the choice problem of protection options using the example data of uranium mine described in *ICRP Publ.55.*

AHP Methodology

The main problem in decision making is the structuring and analysis of complex multicriterion decision problems. The areas in which AHP is applied are diverse and numerous since its introduction due to the practical nature of the method suitable for solving complicated decision problems[7,8]. This section presents a brief summary of the methodology.

The AHP starts by decomposing a complicated decision problem into a hierarchy ; each level consists of manageable elements and each element is decomposed into more detail set of elements. The decomposing process continues down to the most specific elements of the problem, the decision variables, which are represented at the lowest level of the hierarchy. To structure a decision problem hierarchically is an effective way of dealing with complexity and identifying the major components of the problem. One of the major advantages of the AHP is the flexibility it allows an analyzer in constructing a hierarchy to fit his needs under the decision environment.

The AHP technique is based on a matrix of pairwise comparisons between the criteria n and, for each criterion, a matrix of pairwise comparisons between the alternatives m (options) with respect to that criteria. The first matrix is solved to obtain the normalized eigenvector, which provides the relative weights (w_i,

$\cdots, w_n)$ for each criterion. The solution of the second matrix results in the normalized eigenvector, which provides the relative weights ($W_{i1}, \cdots, W_{im}$) of the alternatives with respect to that criterion.

The weight of alternative j is then given by

$$Z_j = \sum_{i=1}^{n} w_i W_{ij}, \quad (1)$$

$$\sum_{i=1}^{n} w_i = 1 \quad and \quad \sum_{i=1}^{m} W_{ij} = 1$$

Where w_i is the relative weight of criterion i, W_{ij} the relative weight of alternative j with respect to criterion i, and Z_j is the global weight of alternative j.

A unique aspect of this approach is that the analysis results can be checked easily as follows: the sum of the values for criterion w_i, and the sum of the values for the final ranking Z_j should be equal one, respectively.

The comparative judgements are applied to construct pairwise comparisons of the relative importance of elements in a given level with respect to a shared criterion in the level above. After structuring of a hierarchy that adresses the decision problem, a scaling method is used to establish priorities among the elements in each stratum of the hierarchy. This is accomplished by asking the decision maker to evaluate each set of elements in a pairwise fashion with respect to each of the elements in a higher stratum using values taken from the scale described in Table 1.

Table 1. Comparison scale of relative importance.

Intensity of Importance	Definition
1	Equally important
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Absolutely more important
2,4,6,8	Intermediate values between the two adjacent judgements

Using this scale[1] the participating managements assess the dominance of each element over the others with respect to each element of the immediate higher levels of the hierarchy [9].

Analysis of Uranium Mine Example

In order to determine an adequate option for radiological protection, the option must be chosen after the effectiveness of all alternatives are evaluated in terms of the protection factors influencing the decision. The example considered relates to the choice of a ventilation system in a small uranium mine. The relevant radiolo-

[1]The nine point scale has been found to be highly reliable because it offers a wide enough range of levels, while the respondents can handle 7 ± 2 in effectively[6].

Table 2. Data for the options considered in the uranium example from *ICRP Publ.55.*

Protection option	1	2	3	4	5
Annual protection cost, $	10400	17200	18500	32200	35500
Annual collective dose, man · Sv	0.561	0.357	0.335	0.196	0.178
Annual average individual doses workers in group, mSv					
A	40.8	28.4	26.0	17.5	15.8
B	34.5	22.3	21.0	12.6	11.3
C	28.9	17.1	16.3	8.4	7.8
Discomfort from Ventilation	no problems	slight	slight	severe	difficult to work

gical protection factors are the annualized protection cost, the annual occupational collective dose arising from external γ irradiation and from the inhalation of uranium particles, the individual dose distribution and the discomfort associated with the high ventilation rate in the galleries and stopes. Five protection options are considered in this analysis, each of which is sufficient to ensure compliance with occupational dose limits. The noticeable feature to this example is that different ventilation rates lead to different doses and have different discomforts or costs associated with them.

The 17 workers have been divided into three groups, to take account of the individual dose distribution, in accordance with their occupancy in various work places of the mine and hence their individual dose levels. The four most exposed workers are group A, four others are in group B, and the remaining nine are in group C. The average individual doses of the workers in each group for the options are shown in Table 2, together with the resultant collective doses.

When such typical factors related to the protection are reviewed in the process of decision making, it is extremely important to express the relevant factors in comparable measure and to identify the corresponding criteria for estimating the factors in the alternatives. In using the AHP analysis technique it is necessary in the first step to set up the decision hierarchy by breaking down the decision problem into a hierarchy of interrelated decision elements. The decision problem is to decide which of five protection options to choose. In the top level is the overall goal of optimal protection option. In the second level are the four criteria (protection factors) which influnce to the goal, and the bottom level are the five candidate options which are to be evaluated in terms of the criteria in the second level. The criteria and options in this method are assumed independent. Figure 1 illustrates a structure of the hierarchy

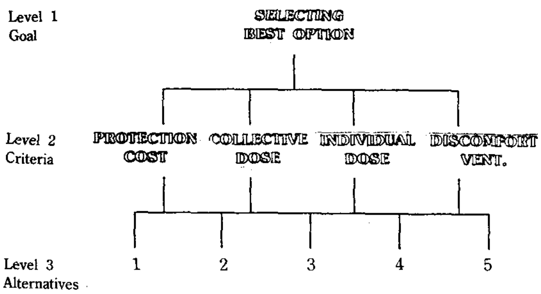

Figure 1. Protection option hierarchy.

for an optimum protection option.

The second step is the elicitation of pairwise comparison judgements: arrange the elements in the second level into a matrix and elicit judgements from the management using the scale given in Table 1. The questions in comparing two criteria are of the following kind: of the two criteria being compared, which is considered more important by the management implementing the option with respect to the overall protection activity ? When comparing the importance of four criteria dimensions, it is desirable to use the checking tabular in Table 3 as the indicater of protection performace.

Each row in this tabular compares two elements. For example, in the right-hand column of the first row, a check in column 3 means that the management believe the collective dose is moderately more important than the protection cost. And a check in column 1 means that the two elements are of equal importance. The use of descriptions as for the intensity of importance in Table 1 is actually more effective than that of importance values 1, 3, ⋯, 9.

The major radiological protection factors that need to be taken into account in decision are the annual protection cost, the annual collective dose, the individual dose distribution and the discomfort from high ventilation rate. The four protection criteria are prioritized by considering relative contribution of criteria with respect to its improtance on the objective.

As for the discomfort from ventilation, the prioritization was done by considering relative degree of aversion associated with the operations of ventilation systems. Comparing the five elements with respect to the extent of discomfort leads to the comparison matrix shown in Table 5.

Table 3. Checking tabular for the category that most closely describes the position the management hold.

	9	7	5	3	1	3	5	7	9	
Protection cost	–	–	–	–	–	–	–	–	–	Collective dose
Protection cost	–	–	–	–	–	–	–	–	–	Individual dose
Collective dose	–	–	–	–	–	–	–	–	–	Individual dose
Protection cost	–	–	–	–	–	–	–	–	–	Discomfort ven.
Collective dose	–	–	–	–	–	–	–	–	–	Discomfort ven.
Individual dose	–	–	–	–	–	–	–	–	–	Discomfort ven.

Table 4. Pairwise comparison of the four protection criteria.

	Protection Cost	Collective Dose	Individual Dose	Discomfort Vent.	Priorities
Protection Cost	1	1/3	1/3	1/3	0.096
Collective Dose	3	1	2	1/3	0.251
Individual Dose	3	1/2	1	1/2	0.219
Discomfort Vent.	3	3	2	1	0.435

$\lambda^{max}=4.19,\ CI=0.06$

Table 5. Pairwise comparison of discomfort from ventilation.

	no problem	slight	slight	severe	difficult to work	Priorities
no problem	1	2	2	5	7	0.418
slight	1/2	1	1	3	4	0.223
slight	1/2	1	1	3	4	0.223
severe	1/5	1/3	1/3	1	2	0.083
difficult to work	1/7	1/4	1/4	1/2	1	0.053

$\lambda^{max}=5.022,\ CI=0.0055$

λ^{max} is the largest eigenvalue of the pair wise-comparison matrix A which satisfies $\lambda^{max} \geqq n$, where equality holds for the perfectly consistent case only. A consistency index is defined as $CI=(\lambda^{max}-n)/(n-1)$, which represents the deviation from consistency[6].

The closer λ^{max} is to n(the dimension of comparison matrix) the more consistent is the result, and CI of 0, 1 or less is considered acceptable.

As in table 4, the collective dose is, for example, moderately more important than the protection cost, insert 3 in the first column of the tabular.

And insert the reciprocal 1/3 where the column of the collective dose meets the row of the protection cost. To determine the priorities of relative importance for the protection criteria, multiply the four elements in each row of Table 4, and take the fourth root and normalize the resulting numbers.

The next step is the pairwise comparisons of the elements in the lowest(bottom) level. The elements to be compared pairwise are the protection options with respect to how much better one is than the other is satisfing each criterion in the second level. The matrix of pairwise comparisons of the criteria in this case is shown in Table 6, along with the resulting priorities.

The global priorities to the problem as in Table 6 was obtained by multiplying the ele-

Table 6. Global priorities for protection options.

Options	Protection criteria (priority)				
	Protection Cost (0.10)	Collective dose (0.25)	Individual dose (0.22)	Discomfort ventilation (0.43)	Global Priorities
1	0.322	0.080	0.080	0.418	0.250
2	0.207	0.162	0.162	0.223	0.192
3	0.231	0.181	0.181	0.223	0.204
4	0.120	0.281	0.281	0.083	0.180
5	0.120	0.296	0.296	0.053	0.174

ment in each row with each priority of the protection criterion and taking the sum of the rows. This priority reveals the particular option to be implemented whose desiredness to the overall protection requirments is the greatest. These results are somewhat different from those of the methods described in *ICRP Publ.55* and of our previous study using the goal programming[10] because, in this method, the criterion on the discomfort from ventilation is highly accentuated than other factors, as 0.43.

Discussion

The prioritization process carried out in the above section pointed to the protection alternative which should be adopted as an optimum options. Discomfort from ventilation, in this example, played the most improtant roles in choosing an option. It is clear that tradeoffs exist between occuaptional doses and discomfort from ventilation, so that an explicit treatment of strategic factors based on the scrutiny considering the real situations would be highly desirable.

In the example of uranium mine the three protection criteria except the qualitative element of discomfort are composed of quantitative values which are acquired as a measurable units. As an other approach, we utilized the given measurement values to evaluate the relative importance of the five options in terms of their ratios, by using the concept of utility functions[4]. For each factor a single attribute utility of 0 was assigned to the worst value, the highest cost, highest collective dose etc., and a single attribute utility of 1 was assigned to the best value, the lowest cost, lowest collective dose etc. And a single attribute utility in the range of value 0 to 1 was assigned for all the other performances.

This process yielded the utility values (1, 0.729, 0.677, 0.131, 0) for protection cost from the entries of Table 2, (0, 0.533, 0.590, 0.953, 1) for collective dose and (0, 0.526, 0.582, 0.944, 1) for individual dose, respectively. To obtain the relative weights from the values, the element values for each factor were normalized so that these numbers could be added to unity. In this case, the prioritization values as for the discomfort from ventilation were left in the estimation of global priorities. They were combined and integrated using the criteria priorities of protection factors in Table 4. The results considering the utility values were achieved as (0.220, 0.206, 0.213, 0.187, 0.176), the order of which was not different fromthat of the general pairwise comparison described above.

In this method we used the relative weights which are known from the measurements such as the protection costs and the exposure doses. This approach can reduce the iterations of pairwise comparisons, however it cannot fully reflect the decision environments in which the available resources suchas the budget for protection or the allowable dose (dose constraint) should be considered. While, in this aspect, the goal programming method can be regarded as an effective technique which treats the decision conditions in the forms of various goal values, the method having a few advantages in decision making may impose additional burdens on the management by forcing him toanalyze many aspects of the problem in detail[11].

It was found through reviews that, within the given framework of AHP, constructing a judgement matrix and computing the eigenvector as shown in Table 4～5 is necessary to yield relative importance even with the known measurement, taking into consideration the decision environments for the better evaluation. The judgement obtained from the iterations of pairwise comparisons would definitely differ from facility to facility, that is, the attachment of importance to a certain factor may be varied with the conditions of the facilities considered and the judgement of the management; therefore, the priority cannot be construed as a strict one.

Many other factors relevant to radiological protection can be included in the decision hierarchy according to the characteristics of the problem, and it can be handled with iterative pairwise comparisons. A sensitivity analysis can be conducted using alternative hierarchical formulations, as well as different pairwise comparisons concerning the likely occurrence of the various situations.

Concluding Remarks

The illustrative analysis of selection problem of protection option was implemented with an example data of uranium mine using the analytical hierarchy process. What we have attempted to provide here is an introductory framework to serve as a foundation methodologically, for further application to a large scale problem on radiological protection.

The effort to evaluate and choose the best alternative may be difficult, but it is an improtant task faced by the manager/assessor in his operating facility. It is characterized by multiple and complex objectives measured in incommensurable units and necessitates reasonable choice. However, this approach provides comprehensive guide for decomposability of the problem to be considered and for the analysis of the relevant factors enfluencing a decision.

The procedure described in this paper can be extended to more complex cases such as the construction of protective measures, time-dependent judgements. The conceptual advantage of the AHP approach and the experience of it suggest that further experimentation with this approach could lead to the establishment of an important additional analysis of protection decision models.

REFERENCES

1. ICRP, *1990 recommendations of the International Commission on Radiological Protection*, ICRP Publication 60, Pergamon Press, Oxford (1991).
2. ICRP, *Cost-benefit analysis in the optimization of radiation protection*, ICRP Publication 37, Pergamon Press, Oxford (1983).
3. ICRP, *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 26, Pergamon Press, Oxford (1977).
4. ICRP, *Optimization and decision-making in radiological protection*, ICRP Publication 55, Pergamon Press, Oxford (1988).
5. S. Sa and M. NARITA, "Application of goal programming to decision problem on optimal allocation of radiation workers". *J. Jpn. Health Phys.*, **28**(2) (1993).
6. T. L. Saaty, *The analytical hierarchy process,* McGraw-Hill, New York (1980).
7. F. Zahedi, "The analytical hierarchy process—A survey of the method and its application". *Interfaces,* **16**(4) (1986).
8. L. G. Vargas, "An overview of the analytical hierarchy process and its applications". *European Journal of Operational Research,* **48** (1990).
9. T. L. Saaty, "A scaling method for priorities in hierarchical structures", *Journal of Mathematical Psychology,* **11**(3) (1977).
10. S. SA and M. NARITA, "A goal programming decision model for selection problem of optimum protection option". *J. Jpn. Health Phys.,* **28**(3) (1993).
11. S. M. Lee, *Goal programming for decision analysis,* Auerback Philadelphia (1972).

계층화 의사결정법을 이용한 방사선방호선택 대안결정에 관한 해석적 방법론

사상덕, 成田正邦*

과학기술처, 북해도대학*

요 약

방사선방호의 최적화 검토에 대하여 계층화 의사결정법에 의한 의사결정과정의 예시적 방법론이 제시되었다.

ICRP Publ. 55의 우라늄 광산 환기시스템 결정 사례의 방호데이터를 이용하여 주어진 방호선택대안 가운데 최적안을 도출하는 과정을 나타내었다.

이 AHP 방법은 방사선방호의 최적안 결정에 있어 방사선방호 관리자 또는 의사결정자가 이해하기 쉽고 간편한 방법으로 판단된다.

Key Words : *계층화 의사결정법, 방사선 방호, 최적화*