# A Multiple Objective Decision Analysis Involving Health and Safety Risks: Potassium Iodide Distribution in Nuclear Incidents

Tianjun Feng FengT@uci.edu
L. Robin Keller* LRKeller@uci.edu

The Paul Merage School of Business
University of California, Irvine, CA 92697-3125

April 2006

**Abstract**

This paper presents a multiple objective decision analysis approach to qualitatively and quantitatively evaluate different Potassium iodide (KI) distribution plans for a hypothetical local region. We developed this approach for a National Research Council committee which was charged with figuring out the best means for protecting people against potential thyroid cancer due to the release of radioactive iodine. We first identify an objectives hierarchy, and then develop the single dimensional value functions and the weights for the objectives using a swing weight method. The identification of the largest value gaps between the status quo and the ideally perfect situation helps to develop potential KI distribution plans. We then use an additive value function to assess the performance of these new alternatives with the status quo as a benchmark by computing their overall values. Furthermore, sensitivity analysis for the KI problem shows this approach can create more key insights for the improvement of health and safety decision making processes, and is a useful contribution to the literature on sensitivity analysis in decisions under certainty.

*(Multiple Objective Decision Analysis; Environmental Health and Safety Risk Decision Making; Potassium Iodide (KI); Nuclear Incident; Sensitivity Analysis)*

*Please address all correspondence to L. Robin Keller, The Paul Merage School of Business, University of California, Irvine, CA 92697-3125, USA. E-mail: LRKeller@uci.edu; Phone: 949-824-6348; Fax: 949-725-2835.

# 1. Introduction

Potassium iodide (KI) is an effective and safe measure to protect vulnerable populations from risks of thyroid cancer caused by exposure to radioactive iodine in the event of a nuclear incident. In this paper, we use a multiple objective decision analysis approach to evaluate different KI distribution plans for a hypothetical local region to effectively protect people against potential thyroid cancer due to the release of radioactive iodine.

## 1.1 Background

Several radiation incidents causing human morbidity and mortality occurred subsequent to the adoption of nuclear technologies to generate electricity in the second half of the last century. Radioiodine is one of the major threats to public health in the surrounding territory when a nuclear incident occurs if it is released into the general environment. People exposed to radioiodine could have an increased risk of radiation injury of the thyroid, including thyroid cancer, primarily due to inhalation of contaminated air.

The most serious accident occurred at the Chornobyl nuclear power plant in Ukraine on April 26, 1986, in which huge quantities of radioiodine were released into the environment with a large population. Many subsequent studies on this disaster show that very young children have the highest sensitivity to the risk of thyroid cancer after exposure to radioiodine. UNSCEAR (2000) states that by the year 2000, about 2,000 cases of thyroid cancer attributed to exposure to the Chornobyl fallout had been reported in the area surrounding the nuclear power plant. The vast majority of the people who later got thyroid cancer were four years old or younger (including fetuses) at exposure to the Chornobyl fallout, indicating an extremely low risk to adults.[1]

[1] The children near Chornobyl inhaled contaminated air and ingested contaminated milk and vegetables.

As an important protective measure specifically against radioactive iodine, stable potassium iodide (such as KI) has been proved to be effective to mitigate radiation doses to the thyroid from radioiodine with the occurrence of an accidental or intentional nuclear fallout event. It is extremely important for the most vulnerable people, including children, infants and pregnant and lactating women, to take KI within a few hours before or after exposure to radioiodine, which will block out radioactive iodine from getting into the thyroid and thus help protect from cancer. Furthermore, KI is generally safe except for the relatively few people who have some pre-existing thyroid conditions and iodine allergies.

Like in Chornobyl, nuclear power plants in the United States also contain a source of radioactive iodine. In the event of a very rare serious accident, the radioiodine might create health risks from exposure to a contaminated environment in the vulnerable population and could cause thyroid cancer years later. Further, since terrorism has become a major threat to the homeland security of the United States, nuclear power plants are considered to be potential targets. Therefore, it has become increasingly important to plan how to protect people exposed to radioactive iodine in the event of a nuclear incident from later developing thyroid cancer. Since KI is effective in protecting against thyroid cancer, a KI distribution program has been considered by the US government and associated agencies as part of a nuclear incident preparedness program.

The KI distribution planning process we participated in was initiated by Massachusetts Congressman Edward J. Markey's Law (i.e. Public Law 107-188, Section 127). To satisfy the requirement of this law, the National Research Council (NRC) organized a committee to conduct a study on the best way to distribute and administrate KI in the event of a nuclear incident, funded by the Centers for Disease Control and Prevention (CDC). One of the authors of this paper served as a decision analyst on the committee of experts from a variety of fields, including thyroid cancer physicians, radioactive safety experts, nuclear power plant safety professionals and emergency management experts. The study began on March 27, 2003 and the committee met monthly until September, 2003, at National Academy of Sciences Offices, primarily in Washington DC (and once at the University of California, Irvine and Woodshole, MA offices). During this period, the committee received oral or written public testimony from experts at several agencies and organizations, such as the U.S. Nuclear Regulatory Commission, EPA (U.S. Environmental Protection Agency), FEMA (Federal Emergency Management Agency), etc. In December 2003, the committee submitted their report for publication as the 2004 peer-reviewed book entitled Distribution and Administration of Potassium Iodide In the Event of a Nuclear Incident.

### 1.2 Research Focus from a Decision Analysis Perspective

While the ultimate task for the National Research Council committee was to find the best solution to the distribution and administration of KI in the event of a nuclear incident, the main purpose of this paper is to demonstrate how a decision analysis process can complement health risk assessment to improve environmental decision making by using the KI decision problem as an example application. Based on the goal of our study, we cover the following in this paper:

*What role can decision analysis techniques play in environmental health and safety risk assessment and management issues?* When people are faced with environmental risk decision making problems, it may be technically or politically difficult to assess associated risks due to the qualitative and non-numerical possible outcomes. Some systematic decision structuring methods can be employed to formulate the environmental decision problems and evaluate different alternatives. In particular, the multiple objective decision analysis approach was used in this paper to show the committee that a decision analysis process can help decision makers analyze the KI problem effectively.

*What is the typical framework of a multiple objective decision analysis approach which can be implemented for environmental and health risk management problems?* As a systematic decision making methodology, the multiple objective decision analysis approach has been widely used in various fields (see the literature review in Section 2). We provide a typical framework for the multiple objective decision analysis approach to evaluate environmental decision problems in Figure 1 of Section 3. Then, the KI decision problem is used as an application of this framework for environmental decision making problems.

*What key insights can a multiple objective decision analysis process provide decision makers for environmental and health risk management decisions?* People can not solely rely on decision analysis methods and expect those approaches to make decisions for them. However, a decision analysis process can be useful if it provides decision makers some key insights and assists them in making decisions. This is important for environmental issues because in many cases decision makers do not have a dominant option that is best on all objectives. Also different stakeholders have different preferred actions, often due to different views of the tradeoffs between objectives. The multiple objective decision analysis approach is shown to create key insights by providing flexibility and enabling sensitivity analysis in the KI decision problem, as addressed in Section 4.

## 2. Literature Review

There is a large body of literature on decision analysis applications,[2] many of these decision problems are complicated because they involve environmental health and safety risks and the implementations of alternatives usually are constrained by legal, political or resource

---

[2] See Corner and Kirkwood (1991) and Keefer, Kirkwood and Corner (2004) for surveys of this literature.

requirements. Decision analysis has been discussed in the literature as a tool to help decision makers assess environmental issues in a step-by-step process and aid them to make decisions.

This paper fits into the growing literature on the theoretical framework of a multiple objective decision analysis approach and its applications. There have been several important studies developing this specific method with objectives hierarchies to analyze a multiattribute decision problem. Keeney and Raiffa (1976) discuss the identification of the alternatives and the determination of the evaluation measures to assess how well the alternatives attain each objective. von Winterfeldt (1987) provides an introduction to the objectives hierarchy method (which he calls value tree analysis) from a decision analysis perspective. Keeney (1992) summarizes guidelines for constructing objectives when alternatives are being evaluated. Kirkwood (1997) provides details for building multiple objective decision models.

In some situations, decision problems involve multiple stakeholder groups with different objectives. Thus it may be useful to characterize the objectives of different stakeholders for evaluating those decision problems. Winn and Keller (1999, 2001) present a multiobjective multistakeholder decision modeling methodology to construct decision problems systematically and capture the complex and dynamic nature of decision frame timelines for multiple stakeholders. They apply this approach to the Starkist's dolphin-safe decision and MacMillan Bloedel's no-clear-cutting forestry decision. Keeney et al. (1987) characterize an objectives hierarchy for the former West Germany's energy supply decision problem by combining the divergent views of multiple stakeholders together into one hierarchy.

In a multiple objective decision analysis process, decision makers may need to quantify the performance of each alternative on the objectives. Thus two main tasks are involved in the evaluation process: specifying value functions and eliciting weights. Keeney and Raiffa (1976) show that an additive-multiplicative decomposition can provide an appropriate value function for evaluating alternatives of a multiattribute decision problem. Edwards and Barron (1994) propose a simplified weighted-additive value function to model a multiple objective decision analysis process (see Kirkwood 1997, Chapter 4). Dyer and Sarin (1979) provide conditions under which single-dimensional value functions may be separately assessed for an additive multiattribute value function. Our paper uses a weighted-additive value function to calculate the overall values for each planned option since it is relatively straightforward to decision makers. Four weighting methods used in decision analysis are discussed in Borcherding, Eppel and von Winterfeldt (1991): the ratio method, the swing weight method, the tradeoff method and the pricing out method. We use the swing weight method in this paper because it can make the multiple objective decision analysis procedure more flexible and add more insights on tradeoffs to decision makers. See Clemen (1996) and von Winterfeldt and Edwards (1986) for more discussion on the swing weight method.

The multiple objective decision analysis approach has become a widely applied decision analysis tool to support decision makers in a variety of decision making settings, e.g., environmental issues, site choices, business projects, and social affairs, etc. Keeney and Ozernoy (1982), von Winterfeldt (1982) and Keeney and Sicherman (1983) are such example applications in health, safety and environmental decision problems. The first two papers use decision analysis to set standards for different types of pollution to reduce the associated risks, such as ambient carbon monoxide and offshore oil discharges, respectively. Keeney and Sicherman (1983) present a decision analysis model to study technology alternatives to generate electricity (e.g. coal vs. nuclear) when several important evaluation criteria are considered, including economic, environmental, health, safety and social factors. More recently, von

Winterfeldt et al. (2002) employ a decision analysis process to assess and manage potential health risks from electric powerlines to the public. Flüeler (2005) proposes an empirically based and technically sound approach to dynamically manage radioactive waste over the long run.

A multiple objective decision analysis process has also proved to be useful to evaluate different potential facility sites and support decision making. An example is Keeney (1973), which presents a decision analytic model with multiple objectives to help make choices among the different plans for developing the facilities around the Mexico City Airport to attain good air quality. Keeney (1979) discusses how to rank ten possible sites for developing a pumped storage facility in the Southwest using a decision analysis process. Ford et al. (1979) discuss the role of a decision analysis process to evaluate different types of nuclear power plant site selection methodologies. Allett (1986) provides another example, stating that decision analysis is an appropriate technique to conduct environmental impact assessment in a site-selection decision problem for new mines.

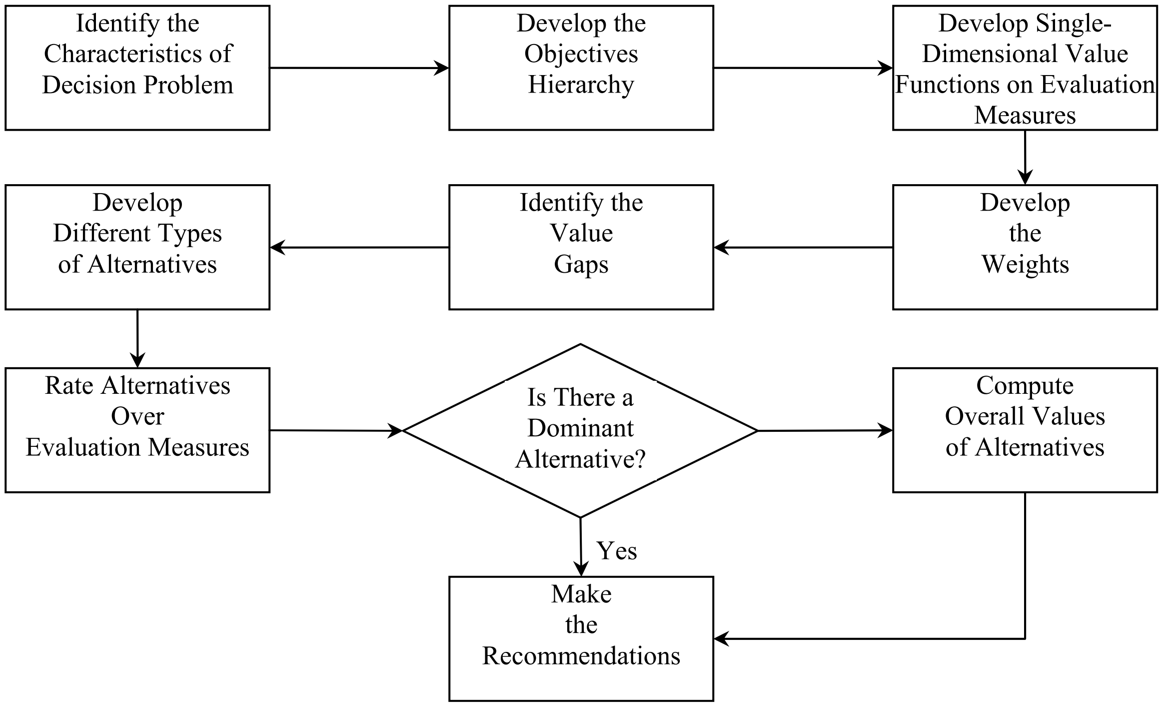
The multiple objective decision analysis approach has also been frequently used for assisting decision makers to evaluate business projects. It has been employed to select effective strategies for the choices of electronic products, such as microcomputer networking in Brooks and Kirkwood (1988), and transmission conductors in Crawford, Huntzinger and Kirkwood (1978). McDaniels (1995) suggests that this approach can play a significant role in the process of evaluating a list of in-season fisheries management options with the involvement of subjective judgments on preferences and likelihoods. Keefer and Kirkwood (1978) conduct this approach to evaluate different allocation plans for operating the budget of the director of a product engineering group, which also contributes to research on resource allocation. Keller and Kirkwood (1999) extend these applications into the not-for-profit domain, in which they discuss the role of a multiple objective decision analysis approach in the merger of two professional societies in operations research and management science. This paper contributes to the literature of decision analysis by providing an application of this approach for complex environmental decision issues involving health and safety risks.

Sensitivity analysis has been widely used in decisions under risk with the aid of decision tree software; however, there are only a few papers discussing sensitivity analysis in decisions under certainty in the literature. Merrick et al. (2005) use a multiple objective decision analysis process to help develop potential plans to improve the quality of the Upham Brook watershed by identifying the largest value gaps between the status quo and the ideally perfect situation, and then perform sensitivity analysis on the value gaps to test the robustness of the analysis to the changes in the weight of one specific objective. Our paper shows how to conduct a more extensive sensitivity analysis by allowing adjustments of the weights on two objectives simultaneously using the sliders created in Excel to examine how the performance of different alternatives changes with the variations in the weights of either one objective or both objectives, which is a useful contribution to sensitivity analysis in decisions under certainty.

## 3. A Multiple Objective Decision Analysis Process

In general, KI is considered to be an effective and safe protective measure against thyroid cancer. Given its efficacy and safety, a number of key stakeholders have called for a study of how to distribute and administer KI effectively in the event of a nuclear incident. A multiple objective decision analysis approach is presented in this section to analyze the KI decision problem. A typical decision analysis procedure which is appropriate for evaluating the KI decision problem is illustrated in Figure 1.

**Figure 1. An Illustration of a Multiple Objective Decision Analysis Approach**




### 3.1 Identifying the Characteristics of the Decision Problem

Stakeholders. The stakeholders for the KI decision problem are mainly government agencies and organizations, including federal level (e.g., EPA, FEMA and FDA), state and local authorities, and the general public. This characteristic makes environmental health and safety risk decision issues different from most business and not-for-profit decision making problems, in which governmental authorities are only a part of the multiple stakeholders and they may not have a prominent impact on decision making. In contrast, for many environmental decision making problems, governmental authorities usually represent the majority of the stakeholders and have relatively dominant power in the decision making process.

"Scientific" perspective. The study of the KI decision problem was initiated from the government officials and agencies, but these political authorities called for a "scientific" perspective from the committee to assess the distribution and administration of KI. The NRC committee members were primarily experts on radiation, thyroid cancer, nuclear power plants and decision analysis, instead of policy experts. This implies that scientific views sometimes play a significant role in environmental decision issues and the stakeholders need the information from scientific reports to improve decision making or to justify their desired action plans.

KI focus. We focus on KI as mandated by Markey's Law. Perhaps because public opinion has framed KI as a "sure-thing" protection based on scientific facts, Congress mandated a focus just on KI. In most cases, an environmental decision making problem involves a number of important issues to be discussed. However, sometimes decision makers are forced to focus on one or two issues while other issues are ruled out of the analysis. While the NRC committee was charged to just consider KI plans, they indirectly broadened the discussion by considering the objective minimizing harm from other aspects of a nuclear incident.

No Consideration of Cost. Minimizing overall costs is usually one key objective in most business decision problems, as well as in a number of municipal, societal and environmental decision making issues. However, for those decision making situations involving serious health risks to the public, monetary cost may not be considered as an important evaluation factor, or it may even be excluded, at least in the opinion of some stakeholders. In the KI problem, some government agencies and officials might refuse to allow cost to be considered in the evaluation process because, in their opinion or because of their agency's mandate, KI costs could almost be ignored compared to the potential severe outcomes to the radiation-affected population.

### 3.2 Developing the Objectives Hierarchy

As discussed above, the key decision makers are mainly government agencies and organizations, at both federal and local levels. Since the KI problem is related to environmental health risks to the public, those governmental stakeholders tend to have some mutual interests and some agreement upon objectives, which turns out to be a positive factor and helps mitigate the conflicts among them. The overall goal is to "Minimize radiation health risks to the public."

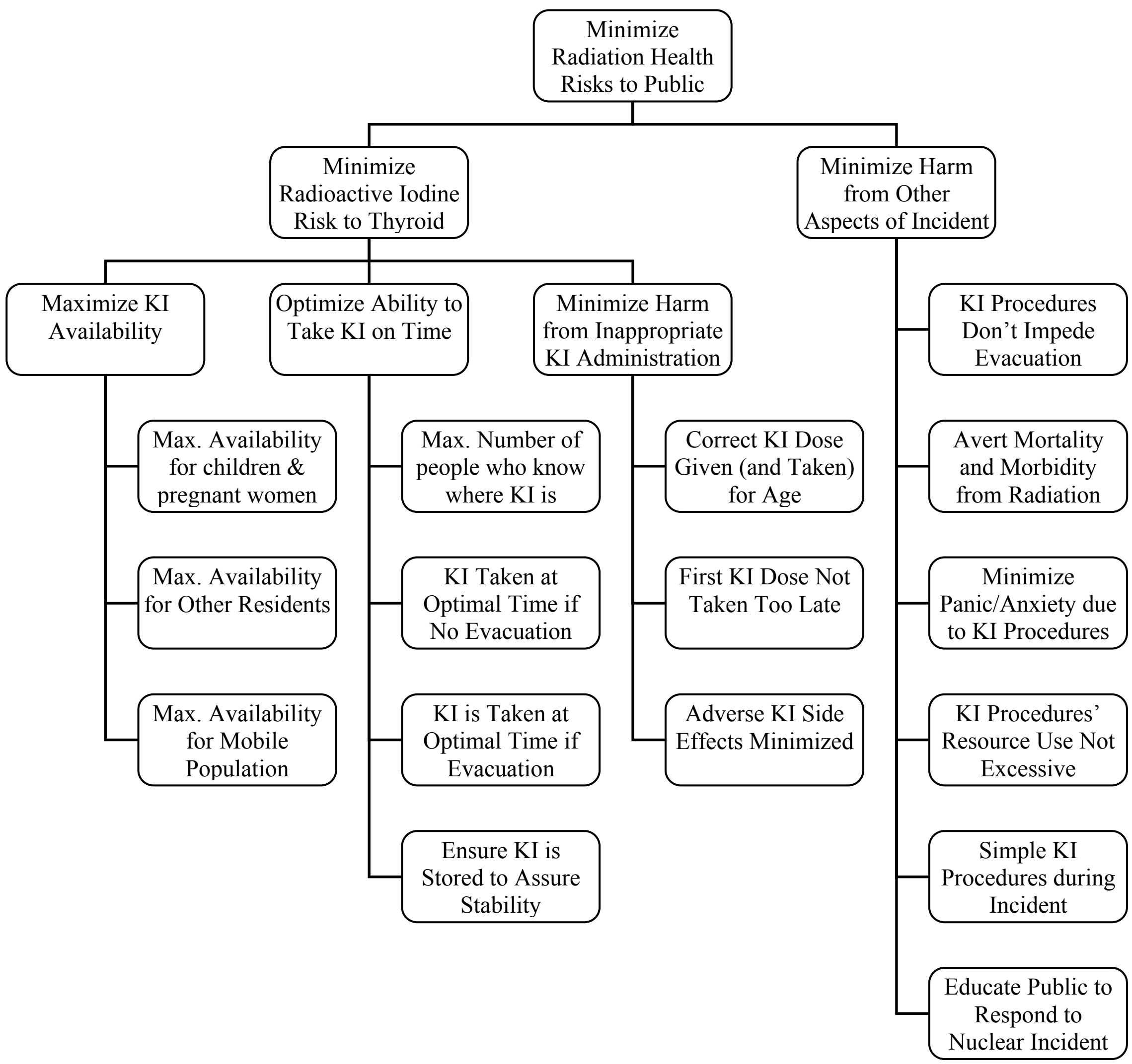
An objectives hierarchy can help key decision makers fully understand the characteristics of decision problems and better evaluate the advantages and disadvantages of different alternatives. According to the guidelines of constructing objectives for evaluating decision alternatives in Keeney (1992), objectives are designed to specify the preferred direction for performance improvement. Moreover, several papers also discuss methods to characterize and generate the objectives for a decision problem structure (See Buede (1986), von Winterfeldt (1987), Winn and Keller (1999, 2001)). Based on these guidelines, an objectives hierarchy of the KI decision problem was developed for a hypothetical local region, as shown in Figure 2.[3]

This objectives hierarchy contains two top-level categories and three levels of objectives and subobjectives; there are sixteen lowest level objectives. From Figure 2, the general objective is to "Minimize radiation health risks to the public," which is followed by two top-level subobjectives, i.e., to "Minimize radioactive iodine risk to thyroid" and "Minimize harm from other aspects of incident." This objectives hierarchy can help government officials quickly grasp the essence of the KI problem. Note that this is a sample objectives hierarchy for officials in a hypothetical local area surrounding a nuclear power plant. For example, as mentioned earlier, the developed hierarchy did not explicitly consider costs (since one committee member very strongly believed that costs should not be considered). However, costs are implicitly covered in the objective "KI procedures' resource use not excessive." The objectives hierarchy may vary from one region to another due to specific situations of each local area. Thus local areas may need to augment or decrease the number of the objectives, modify some objectives, etc. For

[3] This is based on Table 7.2 in the book Distribution and Administration of Potassium Iodine In the Event of a Nuclear Incident (2004), page 147.

example, in a specific region where evacuation could be completed within 24 hours in all scenarios, ensuring multiple-day supplies of KI in homes would probably not be a planning objective. Instead, the objectives might explicitly include "Minimize mortality and morbidity due to radioiodine exposures to thyroids." Therefore, throughout the rest of this paper, we use a hypothetical local region surrounding a nuclear power plant to demonstrate the multiple objective decision analysis approach for the KI problem.

**Figure 2. An Objectives Hierarchy of the KI Decision Problem for a Hypothetical Local Region**



### 3.3 Developing Single-Dimensional Value Functions on the Evaluation Measures

In a multiple objective decision analysis approach, the widely used additive value function is an appropriate method to help further evaluate the KI decision problem quantitatively. Combining weights on the objectives and single-dimensional value functions on the evaluation measures, the additive measurable value function can be written as

$$v(x_1, x_2, \cdots, x_n) = \sum_{i=1}^{n} w_i v_i(x_i),$$

where $v(x_1, x_2, \cdots, x_n)$ is the overall value for an alternative, $x_1, x_2, \cdots, x_n$ are evaluation measures to assess the degree of the attainment of each objective, $w_i$ is the weight assigned to objective $i$ and $v_i(x_i)$ is the single-dimensional value function over evaluation measure $x_i$. (See Edwards and Barron (1994), Kirkwood (1997, Chapter 4), and Keller and Kirkwood (1999) for a review of the additive value function in decision analysis.[4])

To construct the additive value function, it's necessary to figure out the single-dimensional value functions which represent the attainment of different levels on an evaluation measure (i.e., the subjective ratings of one alternative's performance with respect to an objective). One method is to create rating scales on the evaluation measures to assess single-dimensional value functions. Table 1 presents a sample of rating scales on the evaluation measures in the KI decision problem for the subobjective of "Maximize KI availability."[5] In particular, each single-dimensional value function can be scaled to place the values on a 0 to 10 scale, where 0 is minimally acceptable and 10 is best, depending on the degree of the attainment of the specific objective. Note that the end points of the rating scale need not be absolute ratings of the best and

[4] Note that such an additive value function assumes mutual preferential independence, difference consistency and difference independence of one objective from the others. See Theorem 9.23 in Kirkwood (1997) based on the original Theorem 1 in Dyer and Sarin (1979).

[5] A complete table with sample rating scales for evaluating the KI decision problem on all the objectives is given in the Technical Appendix, which can be obtained from the authors. Here we choose one subobjective as an example to illustrate the method of developing the rating scales on the evaluation measures for the KI problem.

worst conceivable levels. Instead, they can be set to be the best and worst levels attainable with a reasonable set of options. For example, on the subobjective of "Maximize availability for children and pregnant women residents," "1 dose per person in stockpile" may receive the lowest level rating of 0 and "85% have extra dose at home now " may become the highest level rating of 10, if this is the range for the set of options being considered.

**Table 1. Sample Rating Scales for Evaluating the KI Decision Problem on the Subobjective of "Maximize KI Availability"**

| | | Maximize KI Availability | | |
|---|---|---|---|---|
| | $v_i(x_i)$ | $x_1$: Max. Availability for Children & Pregnant Women Residents | $x_2$: Max. Availability for Other Residents | $x_3$: Max. Availability for Mobile Population |
| **Selected Points on 0-10 Rating Scale** | 0 | 1 dose/person in stockpile | 0 doses/person in stockpile | 1 dose/child in stockpile |
| | 5 | 50% have extra dose at home now | 10% have extra dose at home now | 1 dose/person in stockpile |
| | 10 | 85% have extra dose at home now | 25% have extra dose at home now | 25% have extra dose at mobile location now |

### 3.4 Developing the Weights

We use the swing weight method in the KI decision problem, which is a theoretically correct way to assess and interpret the weights (Clemen (1996), Kirkwood (1997), von Winterfeldt and Edwards (1986)). In the swing weight method, objectives are placed in rank order of importance, and then importance is more precisely specified via importance weights. By convention, weights are normalized to sum to 100%.[6] Table 2 displays an example with weights for each objective in the KI decision problem for a hypothetical local region using the swing weight method. For example, the subobjective of "Maximize KI availability for children and pregnant women residents" has the largest weight with 0.20.

[6] For example, suppose in the KI distribution problem that decision makers think the objective of "Maximize KI availability for children and pregnant women residents" has the greatest importance weight and all the remaining 15 objectives have the same size importance weight which is 20 percent as great a weight as this objective. Then using the swing weight method, the weight for this specific objective is 100/(100+0.2*100*15)=0.25 and the weight for each of the other 15 objectives is 0.2*100/(100+0.2*100*15)=0.05.

**Table 2. Sample Weights on the Objectives in the KI Decision Problem**

| Objectives | Normalized Weights (Sum = 100%) | Raw Weights (100=max 0=min) |
|---|---|---|
| Minimize Radiation Health Risks to Public | | |
| Minimize Radioactive Iodine Risk to Thyroid **(51%)** | | |
| Maximize KI Availability **(26%)** | | |
| For children and pregnant women residents | 20% | 100 |
| For other residents | 2% | 10 |
| For mobile population | 4% | 20 |
| Optimize Ability to Take KI on Time **(16%)** | | |
| Number of people who know where KI is | 5% | 25 |
| Optimal time if no evacuation | 5% | 25 |
| Optimal time if evacuation | 3% | 15 |
| Storage to ensure stability | 3% | 15 |
| Minimize Harm from Inappropriate KI Administration **(9%)** | | |
| Correct dose given (and taken) for age | 5% | 25 |
| First dose not taken too late | 3% | 15 |
| Adverse side effects (nonthyroid cancer) minimized | 1% | 5 |
| Minimize Harm from Other Aspects of Incident **(49%)** | | |
| KI procedures don't impede evacuation | 10% | 50 |
| Avert mortality and morbidity from radiation or accidents | 18% | 90 |
| Minimize panic and anxiety due to KI procedures | 2% | 10 |
| Avoid excessive resources use in KI procedures | 1% | 5 |
| Simplify KI procedures before and during incident | 8% | 40 |
| Educate public to respond to nuclear incident | 10% | 50 |
| Total | 100% | 500 |

## 3.5 Identifying the Value Gaps

In this section, we identify the value gaps between the status quo and the perfect situation for the KI decision problem which helps to develop potential alternatives for improvement (see Merrick et al. (2005) for more details on value gap analysis). The status quo in the KI decision problem can be considered to be the situation in which there is no distribution of KI.[7] In contrast, Utopia is defined to be an ideally perfect situation for the KI decision problem that achieves each objective completely. As a result, each single-dimensional value in Utopia

[7] Some U.S. regions do have KI distribution programs in existence. The choice of the No Distribution option as the status quo is for a hypothetical region example.

reaches the highest rating 10 and thus Utopia serves as an ideal reference point. Table 3 presents a sample analysis of the value gaps on each objective in the KI problem for a hypothetical local region.[8]

**Table 3. A Sample Analysis of the Value Gaps in the KI Decision Problem**

| Objectives Hierarchy | Weights | No KI Distribution | Value Gaps | Ranking of Value Gaps |
|---|---|---|---|---|
| Minimize Radiation Health Risks to Public | | | | |
| Minimize Radioactive Iodine Risk to Thyroid **(51%)** | | | | |
| Maximize KI Availability **(26%)** | | | | |
| For children and pregnant women residents | 20% | 0 | 2.0 | 1 |
| For other residents | 2% | 0 | 0.2 | 9 |
| For mobile population | 4% | 0 | 0.4 | 6 |
| Optimize Ability to Take KI on Time **(16%)** | | | | |
| Number of people who know where KI is | 5% | 0 | 0.5 | 3 |
| Optimal time if no evacuation | 5% | 0 | 0.5 | 3 |
| Optimal time if evacuation | 3% | 0 | 0.3 | 7 |
| Storage to ensure stability | 3% | 0 | 0.3 | 7 |
| Minimize Harm from Inappropriate KI Administration **(9%)** | | | | |
| Correct dose given (and taken) for age | 5% | 0 | 0.5 | 3 |
| First dose not taken too late | 3% | 10 | 0 | 11 |
| Adverse side effects (nonthyroid cancer) minimized | 1% | 10 | 0 | 11 |
| Minimize Harm from Other Aspects of Incident **(49%)** | | | | |
| KI procedures don't impede evacuation | 10% | 10 | 0 | 11 |
| Avert mortality and morbidity from radiation or accidents | 18% | 10 | 0 | 11 |
| Minimize panic and anxiety due to KI procedures | 2% | 5 | 0.1 | 10 |
| Avoid excessive resources use in KI procedures | 1% | 10 | 0 | 11 |
| Simplify KI procedures before and during incident | 8% | 10 | 0 | 11 |
| Educate public to respond to nuclear incident | 10% | 0 | 1.0 | 2 |

From Table 3, the performance of the status quo (i.e., no distribution of KI) is weak in terms of some objectives, such as "Maximize KI availability" and "Optimize ability to take KI on time," but excellent in terms of the upper-level objective of "Minimize harm from other aspects of the incident." Using Utopia as the reference point, the value gaps can be identified by computing the difference of the weighted values between the status quo and Utopia for each

[8] Note that the value gaps are computed by multiplying the weight on an objective (e.g., the objective of "Maximize KI availability for children and pregnant women residents") with the difference in the ratings between the Utopia and the status quo (i.e, no distribution of KI) on that objective. So the value gap for the objective of "Maximize KI availability for children and pregnant women residents" is 20%*(10-0) = 2.0.

objective, which is useful to develop effective plan options that can improve the attainment of the objectives with large value gaps. The value gaps for each objective and the ranking of the value gaps are included in Table 3 as well. The ranking of the value gaps is based on how large an increase in overall value each specific objective can possibly achieve. For example, the largest value gap is on the subobjective of "Maximize KI availability for children and pregnant women residents," followed by "Educate the public to respond to nuclear incidents." Two of the next largest value gaps relate to optimizing ability to take KI on time.

It is worth mentioning that the status quo performs perfectly on several lower-level objectives in the category of "Minimize harm from other aspects of the incident," which implies that the value gap is zero for each of these subobjectives. This is due to a specific characteristic of the KI problem: no action can completely achieve all of the above subobjectives, e.g., maximizing KI availability will not minimize KI procedures' resource use. Therefore, for potential alternative KI plans suggested by the value gap analysis as discussed in Section 3.6, some of them may score worse on these subobjectives than the status quo. In other words, the improvements for one new alternative on some other subobjectives relative to the status quo are achieved at the expense of the losses in these subobjectives. As a result, when evaluating the new KI plan options, we need to assess the tradeoffs between the decrements they suffer on these subobjectives and the improvements they achieve on others compared to the status quo.

Note that Merrick et al. (2005) present the value gap analysis to identify future plans for the improvement of watershed quality; however, they do not further discuss what the potential programs will be and how to evaluate these alternatives. In this paper, we intend to enhance their technique by proposing a method to evaluate potential alternatives for a decision using the status quo as a benchmark, in which new alternatives are developed by a value gap analysis. In particular, after using a value gap analysis to identify some potential alternatives, we compare the overall performances among all new alternatives over the status quo since the status quo may even have a better evaluation than a new alternative under some circumstances. We will use this method to evaluate different KI alternatives in Section 3.7. We also notice that most literature on decision analysis applications does not assess the status quo when evaluating decisions. This is probably because in most other decisions, the status quo usually can not reach the best possible level on any subobjective and thus there is always a positive value gap for each subobjective. However, it is still possible that a new alternative may score lower on some objectives relative to the status quo. Therefore, our work suggests that considering the status quo is not only necessary for a value gap analysis, but also very important to evaluate potential alternatives for a decision.

The feasible alternatives will likely be constrained by the resources needed (cost, personnel, etc.). For decision models which disregard costs due to political or other constraints, decision makers may want to conduct a subsequent cost-benefit analysis to determine the allocation of the resources on the improvements in the objectives based on the budget constraints since the same quantity of resource may probably lead to different levels of improvements in each objective. In the KI problem, some believed the costs of KI distribution alternatives could be almost ignored as discussed earlier due to the potential critical morbidity and mortality outcomes, though local authorities will most likely need to consider them in the decision making process.

### 3.6 Developing Different Types of Alternatives

After identifying the value gaps, the next step is to develop effective options that focus on the improvement of those objectives with the largest value gaps. For a hypothetical local region discussed above, the committee seeks potential alternatives with large improvements in these objectives, including "Maximize KI availability for children and pregnant women residents," "Educate the public to respond to nuclear incidents," etc. Meanwhile, according to the report from the scientific experts on the committee, the best timeline to administer KI to the potentially affected population near nuclear facilities is just before, concurrently with, or within a few hours after exposure to radioactive iodine. To be responsive to the possible radioiodine releases of a nuclear incident and target the large value gaps, the committee developed three different sample alternatives for a hypothetical local region shown in Table 4.

**Table 4. Three Sample Alternative Plans of the KI Decision Problem**

| Plans | Description |
|---|---|
| MM | Predistribute KI tablets inserted in Mass Mailing to households in KI planning zone (KIPZ); additional stockpiles at reception centers |
| VP | Predistribute to individuals in KIPZ via Voluntary Pickup; additional stockpiles at evacuation reception centers outside KIPZ |
| RC | Stockpile at evacuation Reception Centers outside KIPZ |

Both the first and second options recommend the predistribution of KI to all or segments of the potentially affected population as part of the preparation for responding to a nuclear incident. In particular, the first plan involves direct distribution to individuals or groups by mail or door to door, while the second one institutes voluntary programs for people to pick up KI at several locations, such as government agencies, county health offices and local pharmacies. It is obvious that predistribution can make KI immediately available to people exposed to radioiodine at the time of a nuclear incident and help educate people how to respond, which implies that these two options can improve the performance on the objectives with the large value gaps. But predistribution also has some disadvantages. Based on the coverage statistics of KI predistribution programs in the committee report, well less than 50 percent of the potentially affected people have participated in past voluntary pickup programs. Another technical difficulty is how to determine the size or location of the geographic area which is necessary for KI predistribution. In addition, those who receive KI from predistribution need instructions in its purpose, proper storage and use. Finally, at the time of an incident, those who received predistributed KI might not be able to find it.

Another primary option is stockpiling KI at evacuation reception centers outside the KI planning zone (KIPZ), from which it is dispensed to the potentially affected populace before, concurrently with, or immediately after a radioactive iodine incident. This option not only increases the availability of KI to the affected population, but also leads to better control of KI administration and better recordkeeping. However, stockpiling does not perform well in the relatively rare instances in which evacuation would be impractical, undesirable, or delayed. There are some other relevant issues as well, such as the location of the stockpiles.

Note that these three options above are not a complete list of feasible plans for a local area surrounding a nuclear power plant. For example, a combination of some mechanisms above may form another practical plan in the KI distribution, such as mass mailing plus voluntary pick-up. For the illustration, we concentrate on these three basic and generic options. Furthermore, a local area may develop its own specific alternative actions for a KI distribution program based on the characteristics of this area, such as geography, population density, meteorological conditions and other characteristics related to nuclear power plants.

### 3.7 Evaluating the Alternatives and Making the Recommendations

With new alternatives developed, we provided the National Research Council committee with a template for the performance of different KI distribution plans using the status quo as a benchmark, as shown in Table 5.[9] To be consistent with the abbreviations of the three above alternatives, we use "ND" to represent the status quo in the KI problem, i.e. no KI distribution, for the rest of the paper.

[9] Note that the sliders in Table 5 are not needed for evaluating different alternative plans in this section. We will discuss the use of sliders in Section 4.2.2 to demonstrate two-way sensitivity analysis in the KI decision problem.

**Table 5. A Template for Evaluating the Alternative Plans in the KI Decision Problem**

| Objectives | Sliders | Normalized Weights (Sum = 100%) | Raw Weights (100=max 0=min) | How Well each Plan Meets Each Objective (Rate from 0 to 10 = best) MM | VP | RC | ND |
|---|---|---|---|---|---|---|---|
| Minimize Radiation Health Risks to Public | | | | | | | |
| Minimize Radioactive Iodine Risk to Thyroid | | | | | | | |
| Maximize KI Availability | | | | | | | |
| For children and pregnant women residents | | | | | | | |
| For other residents | | | | | | | |
| For mobile population | | | | | | | |
| Optimize Ability to Take KI on Time | | | | | | | |
| Number of people who know where KI is | | | | | | | |
| Optimal time if no evacuation | | | | | | | |
| Optimal time if evacuation | | | | | | | |
| Storage to ensure stability | | | | | | | |
| Minimize Harm from Inappropriate KI Administration | | | | | | | |
| Correct dose given (and taken) for age | | | | | | | |
| First dose not taken too late | | | | | | | |
| Adverse side effects (nonthyroid cancer) minimized | | | | | | | |
| Minimize Harm from Other Aspects of Incident | | | | | | | |
| KI procedures don't impede evacuation | | | | | | | |
| Avert mortality and morbidity from radiation or accidents | | | | | | | |
| Minimize panic and anxiety due to KI procedures | | | | | | | |
| Avoid excessive resources use in KI procedures | | | | | | | |
| Simplify KI procedures before and during incident | | | | | | | |
| Educate public to respond to nuclear incident | | | | | | | |
| **OVERALL VALUE (SUMPRODUCT OF WEIGHTS TIMES RATINGS)** | | | | | | | |

We explained to the NRC committee how to use the template to evaluate different alternatives in the KI problem. The first step is to rate how well each option does on each objective by using the value rating scales on the evaluation measures in Table 1. For instance, the "MM" option receives 10 for the objective of "Maximize the availability of KI for children and pregnant women residents" since it can make at least 85% of the households have an extra dose at home and thus completely meet this objective. Second, it is important to check whether one option is dominating or dominated compared to other options over all objectives. This option has the first priority to be considered for implementation if it is a dominant alternative, or it should be seriously considered to be eliminated from the set of choices if it is a dominated plan. However, in most cases there is no dominant or dominated option over all objectives. Therefore, the next step is to compute the overall value of an option by multiplying the weight of an objective with the rating of the plan's performance on the objective, then summing these products over all objectives. As a result, the alternative with the highest overall value would be the one recommended by using a multiple objective decision analysis approach.

**Figure 3. Sample Evaluation of Different Alternative Plans in the KI Decision Problem**

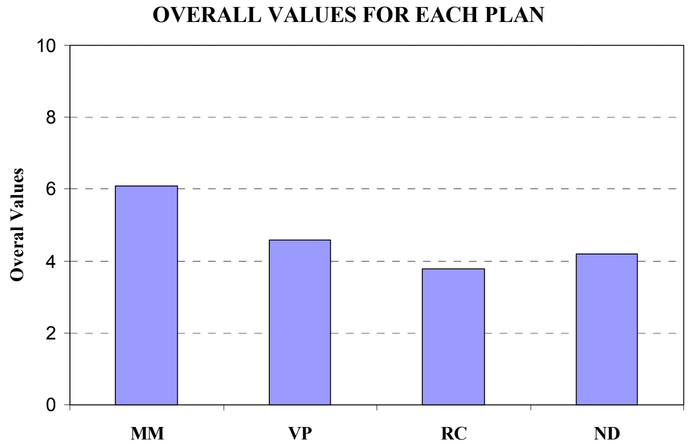



Figure 3 displays the sample overall values of different alternative plans in the KI problem.[10] We can see that for this hypothetical region, the overall values of the "MM" option (6.10) and the "VP" option (4.58) are both higher than that of the "ND" option (4.20), i.e., the status quo. However, it is interesting to find that the "RC" option (3.77) performs even worse relative to the "ND" option.[11] As discussed in Section 3.5, it is because the improvements of the "RC" option over the "ND" option on some objectives (i.e., "Optimize ability to take KI on time," etc.) are offset by even larger decrements on some other objectives (i.e., "Avert mortality and morbidity from radiation or accidents," etc.). This further implies that it is critical to consider the status quo in decision problems. Therefore, in this specific case, KI predistribution in mass mailings would be recommended to decision makers for implementation. Note that the "MM" option improves the two objectives of "Maximize the availability of KI to children and pregnant women

[10] The sample data used to compute the overall values of different alternatives is provided in the Appendix. The spreadsheet given to the NRC committee was set up to automatically graph the overall values once weights and value ratings were entered.
[11] Note that obviously, for a different local region, new alternatives may all perform better than the status quo.

residents" and "Educate the public to respond to nuclear incidents" (i.e., with the first and second largest value gaps) by receiving 10 and 8 on them, respectively.

Note that this is a sample result for a hypothetical local region. The final recommendations will probably be different if there are some changes in the characteristics of the KI decision problem, such as a different region with distinctive regional characteristics, a different objectives hierarchy, a different allocation of weights or a different list of improvement options. Thus decision makers need to use the multiple objective decision analysis approach carefully to assess decision alternatives based on the specific characteristics of the decision problem.

## 4. Key Insights from a Decision Analysis Perspective

Throughout section 3, the KI decision problem has been analyzed and evaluated by using a multiple objective decision analysis approach. The purpose of addressing the KI decision problem from a decision analysis perspective was not to identify the best generic one-size-fits-all approach for key decision makers and to make decisions for them, but to provide them with a useful analysis tool and some key insights which they need to consider to help improve their decision making process. Sometimes key insights may trigger decision makers to analyze a decision problem from a new angle and help them understand it more clearly and completely.

### 4.1 Build Flexibility

The multiple objective decision analysis approach presented here is adaptable to a variety of environmental health, safety and risk decision making problems, which share major characteristics and have some different characteristics on their own. In other words, one advantage of this approach is that it can be applied in a set of similar environmental decision issues with relatively different venues, though it needs some adjustments due to the differences in some specific characteristics when it is used in different decision problems of the same type.

The KI decision problem is a good example to address the flexibility of a multiple objective decision analysis approach. Since there were strong and divergent opinions among stakeholders in the KI problem about what action plan would be best, the National Research Council Committee members felt that they needed to allow flexibility so that local decision makers could be free to choose their best option. The committee decided to not recommend a single one-size-fits-all KI distribution plan. Instead, they decided to present in the Appendix of their book the decision analysis template described here for local decision makers to use. For example, the analysis in Section 3 is assumed to be implemented in a hypothetical local region, surrounded by its KI Planning Zone (KIPZ). In practice, this local region could be like any of the following three stylized local areas surrounding nuclear power plants: urban sites, suburban sites and rural sites. In particular, these three types of local regions differ from each other in the following aspects: population concentration and structure, transportation system, climate, school and medical system, and other features related to evaluating KI plans. For example, regarding population density and structure, an urban site represents a KIPZ with a large, highly concentrated, permanent population that is increased during the week from the influx of large numbers of workers and families from the surrounding area. In contrast, a suburban KIPZ usually contains a few rapidly developing counties that are on the outer fringes of a major metropolitan area and it is populated primarily by a mixture of young families, while a rural KIPZ might have mainly agricultural uses with a thinly-distributed and generally middle-aged population.

Therefore, KI plans in these three distinctive local areas are three different decision problems due to the tremendous regional differences; however they can be considered as a generic type of decision problem because the main issue for all of them is to assess KI plans in a specific local region. The multiple objective decision analysis approach can readily be used in any evaluation process of these three local regions with the same modeling framework. No doubt that the alternatives, the objectives hierarchy or the rating scales may be different for different geographical areas and different regional characteristics may affect the performance of the same KI plan. But this approach is considered to be effective partly in that decision makers can use the same analysis process to assess generic types of decision problems by involving revised alternatives, objectives and rating scales for each specific scenario.

Furthermore, some decision models classify outcomes with qualitative, non-numerical, scales or just identify the objectives of different stakeholders. One inherent problem of these decision methods is that decision makers may have difficulty understanding how to process a large magnitude of qualitative information. This could lead to a biased decision making process for the key stakeholders. Compared to these decision methods, a multiple objective decision analysis approach builds a simple and straightforward procedure to quantify the performance of different alternatives on the objectives and aid decision making. It can also be used (without proceeding to calculations) to portray the decision qualitatively, if desired.

### 4.2 Create Ability to Ask "What If?" Questions

Most environmental decision problems involve health risks and political issues, thus it is likely that there does not exist a unanimously agreed upon desirable alternative to implement. Accordingly, environmental decision makers need "wiggle room" to understand potential tradeoffs and interactions among the alternatives on the objectives and choose the option which can satisfy the interests of stakeholders and requirements of environmental, health and political aspects to the highest degree. The multiple objective decision analysis approach can give decision makers answers to "What If?" questions through sensitivity analysis.

In the KI problem, at first some NRC committee members thought that a single plan would be recommended based on our initial analysis. The committee found that no single plan would be sufficient after they conducted sensitivity analyses in the spreadsheet provided by us to see how sensitive the choice of the best plan was to the assumptions, particularly on the weights. It became obvious as the committee did sensitivity analyses, that the optimal choice would vary by regions (i.e., different action plans would be better for different regions). So the committee decided to provide flexibility by providing a template, which could be filled in by local region stakeholders. Next we present sensitivity analysis for a specific hypothetical local region.

### 4.2.1 One-way Sensitivity Analysis

Corresponding to the more familiar sensitivity analysis in decisions under risk, we refer to one-way and two-way sensitivity analysis in decisions under certainty as sensitivity analysis on the weights of one objective and two objectives, respectively. Note that the KI example is modeled as a decision problem under certainty in this paper.

It is well known that sensitivity analysis is a useful tool in decisions under risk. However, there is not much discussion on sensitivity analysis in decisions under certainty in the literature. This is partly because people have few choices of proper software to perform sensitivity analysis for decisions under certainty,[12] unlike the situation of decisions under risk with more software available (to name a few, Treeage Pro 2006, Analytica, Precision Tree, etc.), though sensitivity analysis is also important for aiding decisions under certainty. In this section, we discuss the

[12] Logical Decisions® for Windows (LDW) is the only software we are aware of which is designed to allow people to perform two-way sensitivity analysis in decisions under certainty.

creation of sliders in Excel,[13] which helps people perform dynamic sensitivity analysis in decisions under certainty by moving the sliders to adjust raw swing weights on the objectives.

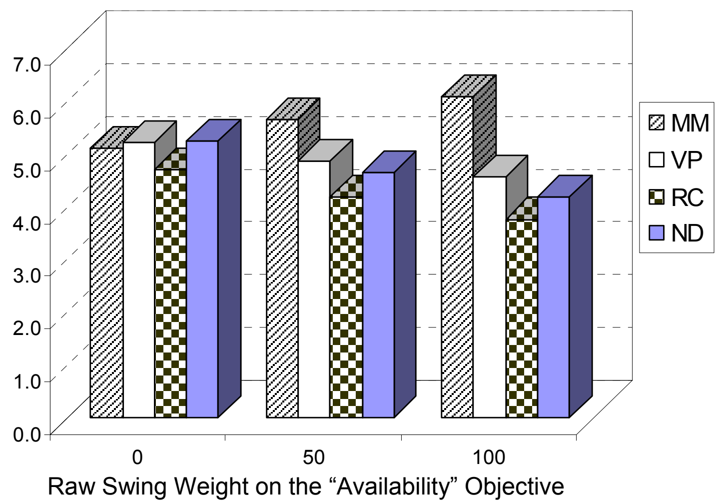
As mentioned before, Table 5 presents a sample template with sliders which can be used to conduct sensitivity analysis in the KI problem. We prepared this Excel spreadsheet with the sliders for the National Research Council committee members, so they could examine the effects of changing weights on the model's recommended actions while they were preparing their recommendations. They were able to visually observe changes in the heights of the bars in the bar graph showing the overall values of each option as they moved sliders for the weights on the objectives. This real-time sensitivity analysis during the committee meetings allowed the committee to ask "What If?" questions as they deliberated on their recommendations.

In Table 5, a slider with the scale 0-100 is created for adjusting a subobjective's raw swing weight without having to directly type in a new raw swing weight number. Obviously, a small adjustment of raw swing weights assigned to one specific objective will change the normalized weight on each objective assuming the raw swing weights of other objectives stay the same and the overall values of all alternatives will also change simultaneously. Therefore, with the help of the sliders, decision analysts can conduct sensitivity analysis by adjusting the raw swing weights of one or several objectives to see how their preference among the options may change with variations in the weights. In addition, we will use the following two objectives with the first and second largest value gaps to demonstrate our method of sensitivity analysis for the KI problem: "Maximize KI availability for children and pregnant women residents," and "Educate the public to respond to a nuclear incident." For brevity, we refer to these two objectives as the "Availability" objective and the "Education" objective throughout the rest of this section.

[13] In contrast to the software of the Logical Decisions® for Windows (LDW), Excel is available on most people's computers and many use it on a daily basis.

We first conduct one-way sensitivity analysis for the KI decision problem to see how the overall values of the alternatives (i.e., mass mailing, voluntary pickup, stockpile at evacuation reception center, and no distribution of KI) change with variations in the weight of one specific objective. For example, suppose decision analysts want to perform one-way sensitivity analysis on the "Availability" objective. The sample data in the Appendix serves as the baseline in the sensitivity analysis here, including the raw swing weights, the ratings for each alternative, etc.

**Figure 4. One-way Sensitivity Analysis on the Raw Swing Weight of the "Availability" Objective**




We can dynamically graph the one-way sensitivity analysis results in the KI decision problem in Excel by moving the slider to adjust the raw swing weight.[14] For illustration, we chose to graph three snapshots in Figure 4 to demonstrate the dynamic one-way sensitivity analysis on the raw swing weight of the "Availability" objective in the KI decision problem: the raw swing weight of the "Availability" objective is 0, 50 or 100, respectively; while the raw swing weights of all other objectives stay constant. From Figure 4, we can clearly see that for this specific hypothetical local region, the performance of the "MM" option is becoming better and better as the raw swing weight of the "Availability" objective increases, while the opposite is

[14] The Excel file can be accessed via our website, see http://webfiles.uci.edu/fengt/KIPlans.xls.

true for the other three alternatives. This result is not surprising since predistributing KI in mass mailings can greatly help improve KI availability for children and pregnant women residents, with a value rating of 10 compared to what the other three options can receive (e.g. the "VP", "RC" and "ND" options receive 2, 2, and 0 on the "Availability" objective, respectively). More interestingly, we find that no KI distribution (i.e., the status quo) is actually preferred when the "Availability" objective is considered to be least important with zero raw swing weight. In addition, when the raw swing weight is 100, it coincides with the base case shown in Figure 3.

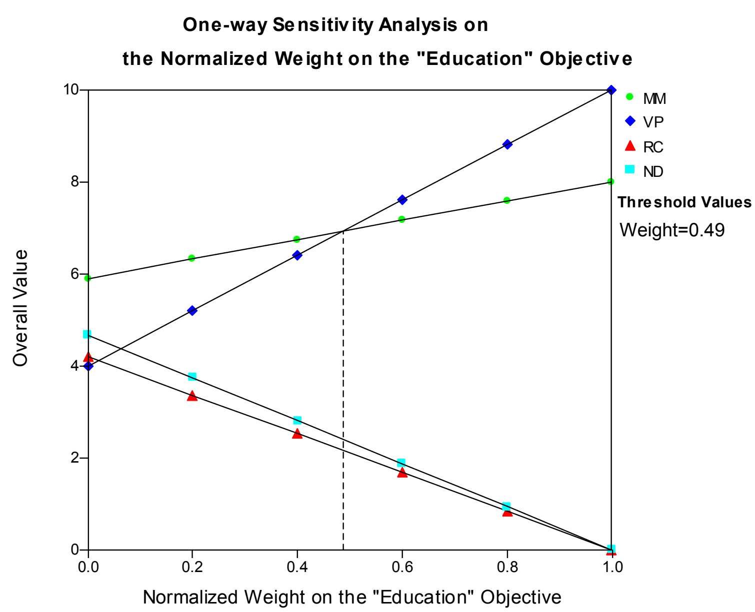
Clearly, in Figure 4, the normalized weight of the "Availability" objective does not vary from 0 to 1.0 (i.e., the range is indeed from 0 to 0.2). In some circumstances, stakeholders may be more interested in sensitivity analysis on the normalized weight of one specific objective varying from 0 to 1.0 since this would provide them more insights regarding decision problems. Suppose now decision analysts want to examine how the variation of the normalized weight on the "Education" objective affects the performances of different alternatives in the KI problem. Figure 5 presents one-way sensitivity analysis on the normalized weight of the "Education" objective varying from 0 to 1.0. Note that all the remaining objectives still retain their original proportions based on their raw swing weights in the Appendix, so all weights add up to 1.0.[15]

From Figure 5, it is clear that the preference among different alternatives changes as the normalized weight of the "Education" objective varies. In particular, if the weight increases, the overall value of the "MM" option and the "VP" option increases, while the overall value of the "RC" option and the "ND" option decreases. Furthermore, both the "RC" option and the "ND" option are never the best and the "VP" option becomes more and more preferable over the "MM" option when the weight is greater than 0.49 onwards. This is mainly because KI predistribution

[15] For example, suppose the normalized weight on the "education" objective is 0.50. Then the normalized weight on the "availability" objective would be (1-0.50)*100/450=0.111 and the same logic could apply to other objectives.

via voluntary pickup is apparently a more effective way to educate people to respond to nuclear incidents than the other three alternatives (e.g. the "VP" option receives a rating value of 10 on the "Education" objective). Note that the sample evaluation result in Figure 3 is consistent with the one-way sensitivity analysis here in that in the baseline example, the "MM" option is the best when the weight on the "Education" objective is 0.10. Similarly, decision analysts can conduct one-way sensitivity analysis on the raw swing weight or normalized weight of any other objective to test the robustness of the results when evaluating different alternatives.

**Figure 5. One-way Sensitivity Analysis on the Normalized Weight of the "Education" Objective**

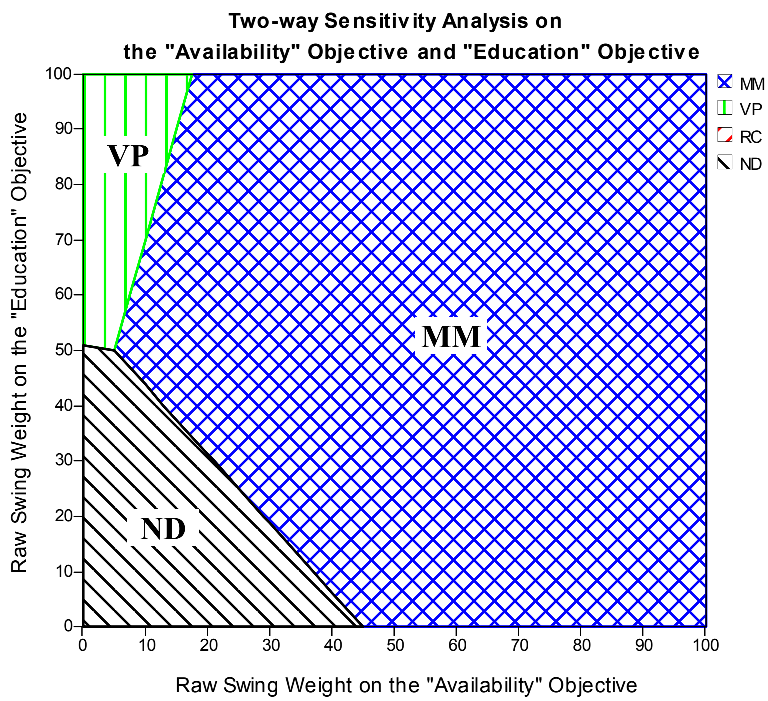



### 4.2.2 Two-way Sensitivity Analysis

As mentioned in section 4.2.1, a method for doing two-way sensitivity analysis in decisions under certainty is to do sensitivity analysis on the weights of two objectives at the same time. The purpose of two-way sensitivity analysis in decisions under certainty is to test how the performances of different alternatives change as the weights of two objectives vary. Suppose decision analysts want to perform a two-way sensitivity analysis on the "Availability" objective and the "Education" objective. Again, we use the sample data in the Appendix as the baseline.

To conduct two-way sensitivity analysis, we vary the raw swing weights of both objectives from 0 to 100 and keep the raw swing weights of the remaining objectives fixed. Figure 6 presents a two-way sensitivity analysis on both the "Availability" objective and the "Education" objective.

**Figure 6. Two-way Sensitivity Analysis on the "Availability" Objective and the "Education" Objective in the KI Decision Problem**




We gain several interesting findings from Figure 6 regarding this specific hypothetical local region. First, the "MM" option (i.e., KI predistribution in mass mailings) performs well on both the "Availability" objective and the "Education" objective, and is the recommended choice when the weight on the "Availability" objective is high (no matter what the weight on the "Education" objective). Second, suppose the weight on the "Availability" objective is low. Then when the weight on the "Education" objective is also low, no KI distribution (i.e., the status quo) becomes the recommended choice, whereas the "VP" option (i.e., KI predistribution via voluntary pickup) is the recommended choice when the weight on the "Education" objective is high. The "VP" option has a benefit on the "Education" objective since communications would go to households, but it is not very good on the “Availability” objective, because people tend not to pick up their allocated doses when distribution is voluntary and people have to pick it up themselves. Third, the “RC” option (i.e., stockpile at evacuation reception center) is never the best for this specific hypothetical example. However, it may be the recommended choice for a different local region.

## 5. Conclusion

A decision analysis process can help stakeholders better understand characteristics of a decision problem and evaluate potential alternatives. Throughout the discussion of the potassium iodide decision problem, a multiple objective decision analysis approach was used to assist National Research Council committee members to evaluate different alternatives effectively. In addition, sensitivity analysis using sliders in Excel created a way for committee members and local decision makers to ask “What If?” questions to analyze the decision problems more completely and then provided them with some key insights to improve decision making. Some committee members liked the spreadsheet-enabled decision analysis approach so much that they kept the file to use in their own work. The KI problem shows how decision analysis can complement risk assessment and evaluation to improve environmental decision making.

The reactions from local stakeholders to the National Research Council report were also positive. For example, a state Radiological Emergency Preparedness Coordinator wrote "The report is perhaps the most balanced and accurate summation of the issues associated with KI distribution that I’ve seen in more than a decade of involvement with the subject...it is gratifying to see that the report...addresses the technical and medical aspects as well as the practical and social considerations involved...the report will prove to be a valuable tool in helping public policy makers confront the questions and concerns of many on both sides of this debate."

Finally, many environmental health and safety risk decision making problems involve governmental authorities representing key stakeholders. Our multiple objective decision analysis of the KI problem also demonstrates how decision analysts can play a significant role in structuring consideration of major political issues focusing on environmental and health risks.

## Acknowledgments

This paper is based on the National Research Council project supported by the National Academy of Sciences and the Centers for Disease Control and Prevention under contract DHHS 200-2000-00629, Task Order Number 16. The project was approved by the Governing Board of the National Research Council. Any opinions, findings, conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the organizations or agencies that provided support for this study. For their great expertise and support, the authors thank the committee organized by the National Research Council: David J. Tollerud, David V. Becker, Lewis E. Braverman, Karen Langley, Timothy J. Maher, Kenneth L. Miller, Christoph Reiners, John J. Russell, Robert Volland, Edward L. Wilds Jr., Sir E. Dillwyn Williams, and Lauren Zeise. (Author Keller served as the Decision Analyst on this pro bono committee.) The authors also thank the attendees of the presentation of this work at the INFORMS conference in Denver in October 2004 for their invaluable comments.

## References

Allett, E. J. 1986. Environmental impact assessment and decision analysis. *The Journal of the Operational Research Society*. **37**(9) 901-910.

Buede, D. M. 1986. Structuring value attributes. *Interfaces*. **16**(2) 52-62.

Borcherding, K., T. Eppel, D. von Winterfeldt. 1991. Comparison of weighting judgments in multiattribute utility measurement. *Management Science*. **37**(12) 1603-1619.

Brooks, D. G., C. W. Kirkwood. 1988. Decision analysis to select a microcomputer networking strategy: A procedure and a case study. *The Journal of the Operational Research Society*. **39**(1) 23-32.

Clemen, Robert T. 1996. *Making Hard Decisions: An Introduction to Decision Analysis.* Second edition, Duxbury Press: Pacific Grove, CA. 547-550 on Swing Weights.

Committee to Assess the Distribution and Administration of Potassium Iodide in the Event of a Nuclear Incident, Board of Radiation Effects Research, Division of Earth and Life Studies, National Research Council of the National Academies. 2004. *Distribution and Administration of Potassium Iodide in the Event of a Nuclear Incident.* National Academies Press, Washington, DC, www.nap.edu. (Keller served as the decision analyst on the committee of scientists.) Available on web: http://books.nap.edu/catalog/10868.html

Corner, J. L., C. W. Kirkwood. 1991. Decision analysis applications in the operations research literature, 1970–1989. *Operations Research.* **39** 206–219.

Crawford, D. M., B. Huntzinger, C. W. Kirkwood. 1978. Multiobjective decision analysis for transmission conductor selection. *Management Science*. **24**(16) 1700-1709.

Dyer, J. S., R. K. Sarin. 1979. Measurable multiattribute value functions**.** *Operations Research.* **27**(4) 810-822.

Edwards, W., F. H. Barron. 1994. Smarts and smarter: Improved simple methods for multiattribute utility measurement. *Organizational Behavior and Human Decision Process.* **60** 306-325.

FDA (Food and Drug Administration). FDA Talk Paper. FDA's Guidance on Protection of Children and Adults against Thyroid Cancer in Case of Nuclear Accident. FDA, Office of Public Affairs, Washington DC, December 10. 2001b.

Flüeler, T. 2005. *Decision Making for Complex Socio-technical Systems: Robustness from Lessons Learned in Long-term Radioactive Waste Governance.* Series Environment & Policy. Vol. 42. Springer: Dordrecht, NL.

Ford, C. K., R. Keeney, C. W. Kirkwood. 1979. Evaluating methodologies: A procedure and application to nuclear power plant siting methodologies. *Management Science.* **25**(1) 1-10.

Keefer, D. L., C. W. Kirkwood. 1978. A multiobjective decision analysis: budget planning for product engineering. *The Journal of the Operational Research Society.* **29**(5) 435-442.

Keefer, D. L., C. W. Kirkwood, J. L. Corner. 2004. Perspective on decision analysis applications, 1990–2001. *Decision Analysis.* **1**(1) 5–24.

Keeney, R. L. 1973. A decision analysis with multiple objectives: The Mexico City Airport. *The Bell Journal of Economics and Management Science*. **4**(1) 101-117.

Keeney, R. L. 1979. Evaluation of proposed pumped storage sites. *Operations Research*. **27**(1) 48-64.

Keeney, R. L. 1992. *Value-Focused Thinking: A Path to Creative Decision Making*. Harvard University Press: Cambridge, MA.

Keeney, R. L., V. Ozernoy. 1982. An illustrative analysis of ambient carbon monoxide standards. *The Journal of the Operational Research Society.* **33**(4) 365-375.

Keeney, R. L., H. Raiffa. 1976. *Decisions with Multiple Objectives: Preferences and Value Tradeoffs.* Wiley, New York.

Keeney, R. L., A. Sicherman. 1983. Illustrative comparison of one utility's coal and nuclear choices. *Operations Research*. 31(1) 50-83.

Keeney, R., Renn, O., von Winterfeldt, D. 1987. Structuring Germany's energy objectives. *Energy Policy* **15** 352-362.

Keller, L. R., C. W. Kirkwood. 1999. The founding of INFORMS: A decision analysis perspective. *Operations Research.* **47** (1) 16-28.

Kirkwood, C. W. 1997. *Strategic Decision Making: Multiobjective Decision Analysis with Spreadsheets*. Duxbury Press. Belmont. CA.

McDaniels, L. T. 1995. Using judgment in resource management: A multiple objective analysis of a fisheries management decision. *Operations Research.* **43** (3) 415-426.

Merrick, J. R., Parnell, G. S., Barnett J. and M. Garcia. 2005. A multiple-objective decision analysis of stakeholder values to identify watershed improvement needs. *Decision Analysis.* **2** (1) 44-57.

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation). 2000. Exposures and Effects of the Chernobyl Accident. *Annex J In Sources and Effects of Ionizing Radiation. Volume II: EFFECTS.* United Nations, New York and Geneva.

von Winterfeldt, D. 1982. Setting standards for offshore oil discharges: A regulatory decision analysis. *Operations Research*. **30**(5) 867-886.

von Winterfeldt, D. 1987. Value Tree Analysis: An Introduction and An application to Offshore Oil Drilling. In P. Kleindorfer and H. Kunreuther (Eds.), *Insuring and managing hazardous risks: From Seveso to Bhopal and beyond*. New York: Springer. 349-377.

von Winterfeldt, D., Edwards, W. 1986. *Decision Analysis and Behavioral Research.* Cambridge University Press: Cambridge, UK, swing weights, 274-5, 286-7.

von Winterfeldt, D., Eppel, T., Adams, J., Neutra, R., & DelPizzo, V. 2002. Managing potential health risks from electric powerlines: A decision analysis caught in controversy. *Risk Analysis*. **24** 1487-1502.

Winn, M. I., L. R. Keller. 1999. Harnessing Complexity, Idiosyncrasy and Time: A Modeling Methodology for Corporate Multi-Stakeholder Decisions. In Wood, D.J. and Windsor, D. (Eds.), *International Association for Business and Society 1999 Proceedings of Tenth Annual conference held in Paris, France*, June 482-487.

Winn, M. I., L. R. Keller. 2001. A modeling methodology for multi-objective multi-stakeholder decisions: Implications for research. *Journal of Management Inquiry*. **10** 166-181.

## Appendix

**Sample Data to Evaluate Different Alternatives for a Hypothetical Local Region**

| Objectives | Normalized Weights (Sum = 100%) | Raw Weights (100=max 0=min) | MM | VP | RC | ND |
|---|---|---|---|---|---|---|
| | | | Description of How Well each Plan Meets Each Objective (Rate from 0 to 10 = best) | | | |
| Minimize Radiation Health Risks to Public | | | | | | |
| Minimize Radioactive Iodine Risk to Thyroid **(51%)** | | | | | | |
| Maximize KI Availability **(26%)** | | | | | | |
| For children and pregnant women residents | 20% | 100 | 10 | 2 | 0 | 0 |
| For other residents | 2% | 10 | 10 | 1 | 0 | 0 |
| For mobile population | 4% | 20 | 0 | 10 | 0 | 0 |
| Optimize Ability to Take KI on Time **(14%)** | | | | | | |
| Number of people who know where KI is | 5% | 25 | 0 | 5 | 10 | 0 |
| Optimal time if no evacuation | 3% | 25 | 10 | 3 | 0 | 0 |
| Optimal time if evacuation | 3% | 15 | 10 | 10 | 10 | 0 |
| Storage to ensure stability | 3% | 15 | 0 | 0 | 10 | 0 |
| Minimize Harm from Inappropriate KI Administration **(9%)** | | | | | | |
| Correct dose given (and taken) for age | 5% | 25 | 0 | 5 | 10 | 0 |
| First dose not taken too late | 3% | 15 | 10 | 10 | 0 | 10 |
| Adverse side effects (nonthyroid cancer) minimized | 1% | 5 | 0 | 8 | 10 | 10 |
| Minimize Harm from Other Aspects of Incident **(49%)** | | | | | | |
| KI procedures don't impede evacuation | 10% | 50 | 0 | 5 | 10 | 10 |
| Avert mortality and morbidity from radiation or accidents | 18% | 90 | 10 | 3 | 0 | 10 |
| Minimize panic and anxiety due to KI procedures | 2% | 10 | 10 | 5 | 10 | 5 |
| Avoid excessive resources use in KI procedures | 1% | 5 | 0 | 5 | 7 | 10 |
| Simplify KI procedures before and during incident | 8% | 40 | 0 | 3 | 10 | 10 |
| Educate public to respond to nuclear incident | 10% | 50 | 8 | 10 | 0 | 0 |
| OVERALL VALUE (SUMPRODUCT OF WEIGHTS TIMES RATINGS) | 100% | 500 | **6.10** | **4.58** | **3.77** | **4.20** |