A Decision Analysis Approach for Risk Management of Near-Earth Objects

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Abstract

Risk management of near-Earth objects (NEOs; e.g., asteroids, comets) that can potentially impact Earth is an important issue that took on added urgency with the Chelyabinsk event of February 2013. Thousands of NEOs large enough to cause substantial damage are known to exist, although only a small fraction of these have the potential to impact Earth in the next few centuries. The probability and location of a NEO impact is subject to complex physics and great uncertainty, and consequences can range from minimal to devastating, depending upon the size of the NEO and location of impact. Deflecting a potential NEO impactor would be complex and expensive, and inter-agency and international cooperation would be necessary. Such deflection campaigns may be risky in themselves, and mission failure may result in unintended consequences.

Considerable work has been applied to identification of NEOs and much thought applied to potential deflection techniques; however, the benefits, risks, and costs of different potential NEO risk management strategies have not been compared in a systematic fashion. We present a decision analysis framework addressing this hazard. Decision analysis, the art and science of informing difficult decisions, has a long and varied history, with roots in economics, business, psychology, statistics, engineering, and other fields. It is inherently multi-disciplinary, especially with regard to managing catastrophic risks. Note that risk analysis clarifies the nature and magnitude of risks, whereas decision analysis guides rational risk management. Decision analysis can be used to inform strategic, policy, or resource allocation decisions.

The basic steps in decision analysis are universal to most rational, systematic decision-making processes. First, a problem is defined, including the decision situation and context. Second, objectives are defined, based upon what the different decision-makers and stakeholders (i.e., participants in the decision) value as important. Third, quantitative measures or scales for the objectives are determined. Fourth, alternative choices or strategies are defined. Fifth, the problem is then quantitatively modeled, including probabilistic risk analysis, and the alternatives are ranked in terms of how well they satisfy the objectives. Sixth, sensitivity analyses are performed in order to examine the impact of uncertainties. Finally, the need for further analysis, data collection, or refinement is determined.

The first steps of defining the problem and the objectives are critical to constructing an informative decision analysis. Such steps must be undertaken with participation from experts, decision-makers, and stakeholders. The basic problem here can be framed as: “What is the best strategy to manage risk associated with NEOs?” The objectives of the risk management decisions (or sequence of decisions) are less clear, especially when the consequences (e.g., misallocation of resources) of an impact or near-miss vary so widely with the asteroid mass, velocity, impact location and timing, among other factors. Some high-level objectives might be to minimize: mortality and injuries, damage to critical infrastructure (e.g., power, communications, food distribution), ecosystem damage, property damage, ungrounded media and public speculation, resources expended, and overall cost. Another valuable objective would be to maximize inter-agency/government coordination.

Some of these objectives (e.g., “minimize mortality”) are readily quantified (e.g., deaths and injuries averted). Others are less so (e.g., “maximize inter-agency/government coordination”), but these can be scaled. Objectives may be inversely related: e.g., a strategy that minimizes mortality may cost more. They are also unlikely to be weighted equally. Defining objectives and assessing their relative weight and interactions requires early engagement with decision participants.

High-level decisions include whether to deflect a NEO, when to deflect, what is the best alternative for deflection/destruction, and disaster management strategies if an impact occurs. Important influences include, for example: NEO characteristics (orbital characteristics, diameter, mass, spin, composition), impact probability and location, interval between discovery and projected impact date, interval between discovery and deflection target date, costs of information collection, costs and technological feasibility of deflection alternatives, risks of deflection campaigns, requirements for inter-agency and international cooperation, and timing of informing the public.

The analytical aspects of decision analysis center on estimation of the expected value (i.e. utility) of different alternatives. The expected value of an alternative is a function of the probability-weighted consequences, estimated using Bayesian calculations in a decision tree or influence diagram model. The result is a set of expected-value estimates for all alternatives evaluated that enables a ranking; the higher the expected value, the more preferred the alternative. A common way to include resource limitations is by framing the decision analysis in the context of economics (e.g., cost-effectiveness analysis).

An important aspect of decision analysis in the NEO risk management case is the ability, known as sensitivity analysis, to examine the effect of parameter uncertainty upon decisions. The simplest way to evaluate uncertainty associated with the information used in a decision analysis is to adjust the input values one at a time (or simultaneously) to examine how the results change. Monte Carlo simulations can be used to adjust the inputs over ranges or distributions of values; statistical means then are used to determine the most influential variables. These techniques yield a measure known as the expected value of imperfect information. This value is highly informative, because it allows the decision-maker with imperfect information to evaluate the impact of using experiments, tests, or data collection (e.g. Earth-based observations, space-based remote sensing, etc.) to refine judgments; and indeed to estimate how much should be spent to reduce uncertainty. Influence diagrams, which are a more efficient way of performing decision analyses than decision trees, are particularly useful in estimating the expected value of information.

Keywords: *near-Earth objects, risk assessment, risk management, decision analysis, policy analysis*

1.0 Introduction

Thousands of near-Earth objects (NEOs; e.g. asteroids and comets) with the potential to impact Earth, and large enough to cause substantial damage, are known to exist [1]. The timing, probability and location of a NEO impact is subject to complex physics and great uncertainty, and consequences can range from minimal to devastating depending upon the characteristics of the NEO and location of impact. Deflection campaigns to divert a potential NEO impactor would be complex and expensive, and inter-agency and international cooperation would be necessary. Such deflection campaigns may be risky in themselves, and failure may result in unintended consequences. If deflection is not successful and a NEO impacts populated areas, or causes ancillary events such as a tsunami, then disaster management would be necessary.

Considerable work has been applied to identification of NEOs and much thought applied to potential ways to deflect them; however, to our knowledge the benefits, risks, and costs of different potential NEO risk management strategies, including disaster management, have not been compared in a systematic and quantitative fashion. The Association of Space Explorers' 2008 report [2] stated:

Failing to provide a decision-making framework before a threatening NEO is discovered will result in lengthy argument, protracted delays, and collective paralysis. Such delays will preclude a deflection and force the world to absorb a damaging – albeit preventable – impact. With the lead time for a decision typically needed at least 10-15 years ahead of a potential impact, we should now begin to forge that vital decision-making capacity.

An informative framework for decisions under risk and uncertainty is called quantitative risk management analysis, or decision analysis. Decision analysis can be used to inform strategic, policy, or resource allocation decisions. It has roots in economics, business, psychology, statistics, engineering, and other fields; and has been applied to a wide variety of difficult decisions in both industry and government policy-making for over 50 years [3]. It is inherently multi-disciplinary, especially with regard to managing catastrophic risks. Decision analysis usually includes risk analysis, which defines and quantifies the nature and magnitude of risks; decision analysis is a broader effort that guides rational risk management.

The basic steps in decision analysis are universal to most rational and systematic decision-making processes (Figure 1), and amount to formalized 'common-sense'. However, note that this process differs from common decision-making approaches that focus on the alternative strategies first, as opposed to defining objectives first. A focus on alternatives will generally not identify the optimal strategy in cases of decisions made under risk and uncertainty, as has been shown in decades of research [4]. The theoretical framework of decision analysis is based in economics and expected utility theory [3], which maintains that a rational decision-maker will seek to maximize utility, or a measure of gains versus losses associated with a decision. Procedurally, a problem is defined, including the decision situation and context. Objectives, based upon what the different decision-/policy-makers and stakeholders (i.e., decision participants) value or deem important, are defined. Quantitative measures or scales (i.e., attributes) for the objectives are determined. Alternative choices or strategies are defined. The problem is then quantitatively modeled, using expected value methods, and the alternatives are ranked in terms of how well they satisfy the objectives. Sensitivity analyses are performed in order to examine the impact of uncertainties, and the need for further analysis, data collection, or refinement is determined. Value-of-information analysis can demonstrate the 'value' of additional or different information collection or research. These steps, as applied to NEO risk management, are described further below.

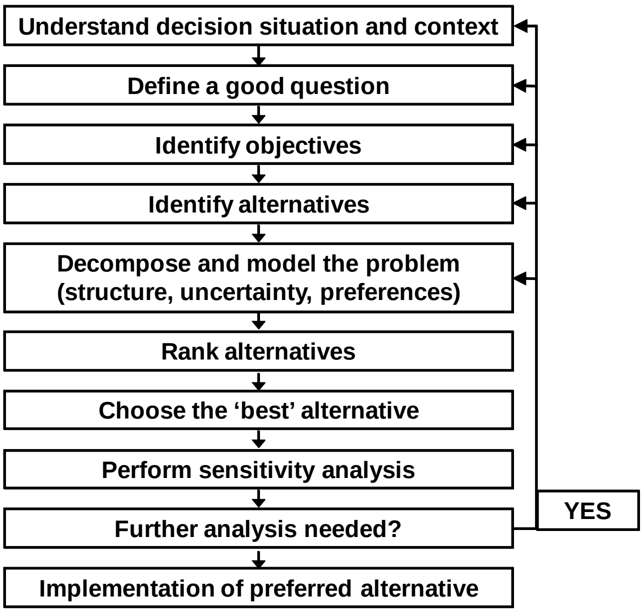

Figure 1: *Decision analysis process*

Although a simple economic analysis has been performed for prevention of human extinction, using a large asteroid impact as an example [5], and other similar explorations have been made, the extensive process of conducting a decision analysis for the NEO impact hazard has not been performed. This will be a complex effort that will require cooperation and funding from multiple international institutions. The remainder of this paper outlines the process that could and should be followed, assuming appropriate interest in a rational decision-making framework. When (not if) a serious asteroid threat occurs, decisions *will* be made - it is up to decision participants to employ a decision analysis approach to inform their decisions in order to make them transparent and defensible.

2.0 Material and Methods

2.1 *Problem Definition*

The first steps of defining the problem and the objectives, termed 'decision structuring', are critical to constructing an informative decision analysis. Such steps should be undertaken in a formal, structured process with participation from experts and decision participants. Involvement of public stakeholders is critical, given the global nature of the hazard and its consequences. To avoid controversy and dispute, NEO decisions ideally should be made with participation by elected representatives of the public, and not unilaterally by technical experts or bureaucratic policy makers.

The basic problem confronting decision makers can be framed as: "What is the best strategy to manage risk associated with NEOs?". "Best" is defined by how well different strategies satisfy the decision objectives, including tradeoffs across these objectives. Therefore, in decision analysis, "best" is not a single-objective concept, such as "What is the best technological means to maximize deflection effectiveness?". After all, the "best" technology may be the most expensive, or it may carry ancillary risks. These tradeoffs should be evaluated in a careful fashion (outlined below).

2.2 *Objectives*

Objectives are decision factors that decision participants care about. As in problem definition, objectives are ideally determined via a structured process. The objectives of NEO risk management decisions (or a sequence of decisions) are not immediately clear, especially when the consequences of an impact or even a near-miss vary so widely depending upon the object's mass, composition, predicted impact site and timing, and so on. As decision analysis is a quantitative process, objectives must be clearly defined and either directly measurable (e.g., financial costs measured in dollars) or scalable (e.g., potential for tsunami damage on a scale from 1 to 10). Practitioners have determined a set of 'rules' for objective definition so that the process and results of a decision analysis are clear [4].

Examples of high-level, 'fundamental' objectives applicable to the NEO issue may include:

- Minimize human mortality
- Minimize human injury

- Minimize damage to critical infrastructure (e.g., power, communications, food production, etc.)
- Minimize ecosystem damage
- Minimize property damage
- Minimize media speculation
- Minimize resource utilization
- Minimize cost
- Maximize inter-agency/government coordination.

Note that some of these objectives (e.g., "minimize mortality") are readily quantified (e.g., deaths averted), while others are less so (e.g., "maximize inter-agency/government coordination"); however, these can be scaled. Costs are addressed in different ways, but many economists would view cost as a resource limitation as opposed to an objective (e.g., if a defined budget exists, what is the most beneficial alternative under this budget?). These objectives have inherent tradeoffs: e.g., a strategy that minimizes mortality probably would not cost the least. A common example is buying an automobile; it is highly unlikely that a single automobile possesses the highest performance, lowest gasoline consumption, lowest cost, highest degree of comfort, and highest degree of safety.

The objectives are also unlikely to be weighted equally. For example, minimizing mortality is probably considered more important than minimizing property damage, and thus would be more heavily weighted. A number of means exist for determining these weights, which depend on the specific characteristics of objectives, amount of time and resources available, and other factors [4]. In any event, up-front participation by experts and decision participants is necessary to define the objectives, the degree of weighting, and the nature of tradeoffs.

These fundamental objectives are distinguished from 'means' objectives. For example, 'maximize deflection effectiveness' may be a means objective that serves to realize the fundamental objective "minimize mortality". This distinction is important, as the fundamental objectives are defined from the values of the decision participants, whereas the means objectives may be determined by technical experts. A qualitative or visual objectives hierarchy helps to distinguish between these types.

Regardless of the objective type, all are quantified via 'attributes'. Attributes are the measures of objectives. As mentioned previously, some attributes have natural units, such as number of lives saved by deflection. Attributes without natural units may be scaled (e.g., 1 to 10), or proxy measures may be used. It is necessary to quantify objectives via attributes in order to define preferences and an ultimate measure of utility for use in the decision analysis.

2.3 *Alternatives*

Alternatives are different actions, in this case, to manage NEO risks. These may involve different technologies or policies which generally satisfy the defined objectives. In the automobile example, Car A may have good fuel economy and a high degree of safety, but deliver poor performance and comfort, while Car B may have poor fuel economy and safety, offset by high performance and comfort.

In the case of NEOs, there are three broad classes of alternatives that relate to different means of detecting NEOs, NEO deflection, and post-impact disaster management. For example, NEO detection might use ground-based or space-based platforms, or different technologies such as optical or radar observation. Deflection may make use of nuclear explosives, kinetic impactors, or gravity tractors. These alternatives involve both policy and technological considerations, and may change over time. It is important to include as many alternatives and combinations of alternatives as is feasible, to avoid unnecessarily constraining the decision analysis. Defining the objectives before alternatives is important, as objective-focused thinking may actually spur development of innovative alternatives. Combinations of alternatives may also be defined, and/or redundancy (e.g., planning a backup mission if a first deflection mission fails).

An additional alternative that is often discussed in the context of other large-scale disasters is insurance. Insurance may have a role in risk management, but insurance is simply a means to transfer risk from affected parties to the insurer. The insurer charges money to accept risk (directly for private insurance, via taxes for public insurance). Thus, insurance is not risk management *per se*; as it only typically addresses the consequences of a risky scenario (i.e., losses). There may be no particular incentive to reduce risk in the case of private insurance, as the insurer makes a profit from a risky situation. As public insurance is funded by public money, there may be more incentive to reduce risk.

2.4 *Modeling the Problem*

To this point, the decision structuring process is largely qualitative. By itself, this partial process may be valuable to help decision participants focus on the most important issues and to foster discussion. However, if a decision analysis is to be conducted, quantitative models must be defined.

2.4.1 Decision Modeling

Decision models are typically constructed using either influence diagrams or decision trees. Figure 2 is an illustration of a high-level influence diagram for the NEO risk management problem. Note than an influence diagram represents the important influential factors in a decision and how they are structured; it is not a flow diagram. Such diagrams are useful to help structure a decision problem, but they also have a logical and computational structure so that calculations can be made. Decision trees are a more linear representation of decision logic and calculations than influence diagrams, but are similar in many ways. The main advantage of influence diagrams is that their hierarchical structure is useful for analyzing complex decisions. A complete influence diagram for NEO risk management decision-making will be much more complex and detailed.

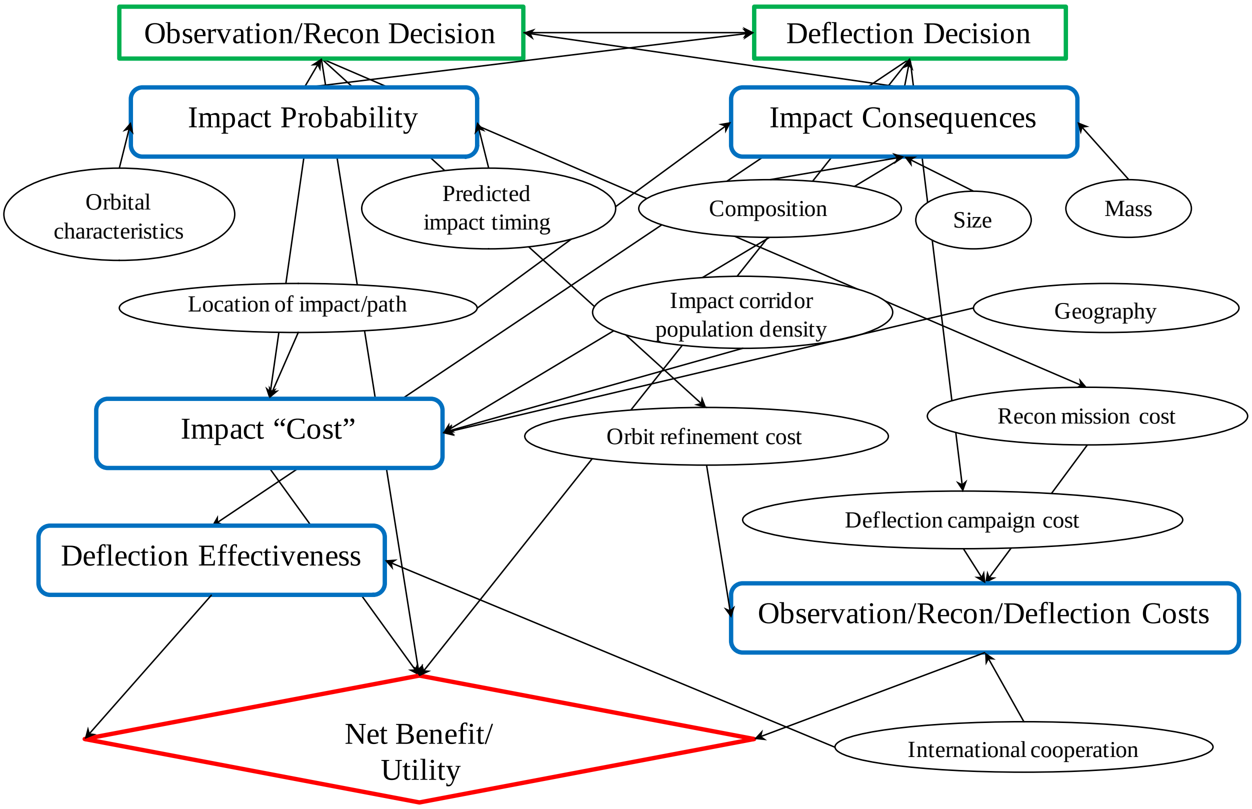

Figure 2: *NEO risk management influence diagram. Rectangles represent decisions, rounded corner rectangles represent intermediate calculations, ovals represent probabilities, and the diamond is the outcome function.*

The calculations in both influence diagrams and decision trees are termed expected value calculations, as they calculate the mean utility (and uncertainty) associated with any particular strategy. The end result of a decision model is a ranked list of how well the different alternatives (with tradeoffs) satisfy the objectives.

2.4.2 Risk and Uncertainty Modeling

Risk is typically defined as a joint function of vulnerability, probability, and consequence [6]. Vulnerability is a state of a system that predisposes it to damage or loss. Probability is the likelihood an event will occur. Consequences are the (usually adverse) effects of an event. Risk assessment is the process of estimating risks under defined scenarios. Probabilistic risk assessment not only estimates risks, but uncertainty associated with those risks.

Researchers have been thinking about risks associated with NEOs for about twenty years. For example, Chapman and Morrison [7] clearly defined different types of damage associated with different sizes of NEOs, and estimated probabilities associated with these events based upon observation and the historical record. However, researchers have not quantified the joint function of vulnerability, probability, and consequence, nor have they quantified uncertainties associated with NEO risks in a way that enables determination of the value of increased research or orbit refinement capability.

As an example, the 300-meter NEO 99942 Apophis had been thought to be one of the NEOs most likely to impact the Earth in coming decades. However, the estimated probability that Apophis will do so has varied greatly over time. Table 1 illustrates the degree of uncertainty.

Table 1: Changes in estimated impact probabilities for 99942 Apophis

Date	Impact Probability	Impact Date of Interest
12/23/2004	0.004	2029
12/25/2004	0.02	2029
12/27/2004	0.03	2029
2/6/2005*	0.0001	2036*
8/5/2006	0.00002	2036
10/7/2012	0.000004	2036
2/28/2013	0.000000007	2036

Source: [1]

*After 2005, the 2029 impact date had been ruled out.

These changes in impact probabilities are dependent upon a number of factors, but the main influence was continued refinement in our knowledge of Apophis' orbital elements. In this case, the estimated impact probabilities initially increased, but have now been reduced to the point so that Apophis is not considered an impact risk in this century. However, it is possible that for other NEOs, additional orbital data will increase the probability of an impact. Additionally, these are deterministic (single-point) estimates, dependent upon actual observation of a NEO. It is likely, for example, that the initial estimates have a larger degree of uncertainty than the more recent estimates (as evidenced by the large swings in estimates in 2004), but this information is not readily available from databases. Two dramatic examples in February 2013 illustrate the high degree of uncertainty associated with risk assessment of NEOs: the dramatic fireball explosion over Chelyabinsk (Russia), which occurred with no warning, and the nearly simultaneous near-Earth flyby of 2012 DA14, discovered less than a year earlier, but with sufficient orbital accuracy to safely rule out any chance of an impact.

Two semi-quantitative scales are commonly used to characterize NEO risk. The Torino Scale is designed to communicate to the public the risk associated with a predicted NEO impact. This scale, which has integer values from 0 to 10, takes into consideration the predicted impact energy of the event as well as the impact probability. The Palermo Scale is used by specialists in the field to quantify in more detail the level of concern associated with a potential impact. Much of the utility of the Palermo Scale lies in its ability to carefully assess the risk posed by less-threatening Torino Scale 0 events, the category of nearly all of the potential impacts predicted to date. Objects are ranked according to their Palermo Scale values in order to assess the degree to which they should receive additional attention (i.e., observations and analysis). This scale is continuous (both positive and negative values are allowed) and incorporates the time between the present and the predicted potential impact, the object's predicted impact energy, and likelihood of occurrence [1]. While these scales are useful for communication, they do not provide the degree of quantitative rigor necessary for probabilistic risk assessment.

Risk modeling as part of a decision analysis would take the form of estimating the joint vulnerability, probability, and consequences of potential NEO impacts. Vulnerability would vary widely depending upon the target geography and energy of the NEO, ranging from inconsequential areas such as remote areas of the oceans (at least with smaller NEOs) to highly vulnerable areas such as the East Coast of the U.S. or much of Europe. Impact probabilities would be based upon orbital observations. Consequences would relate to the objectives defined, and would range from trivial to devastating. Risk analysis techniques that focus on low-probability, high-consequence events will likely be useful [8].

2.4.3 Preference and Utility Modeling

Different individuals and groups have different preferences with regard to the decision objectives. This is termed a preference structure. For example, a particular shopper may prefer a car with high gas mileage to one with high performance, and his spouse may prefer the opposite. In the case of a threatening NEO, a government may value minimization of critical infrastructure damage over ecological damage, whereas an environmental group may well prefer the reverse. Tradeoffs between multiple objectives are evaluated; e.g., the decision participants may be willing to allow ecological damage to occur so that more resources can be allocated to preserving critical infrastructure. Additionally, the way that objectives are combined in a decision analysis may change depending upon the particular problem. If attaining each objective results in a particular utility (an arbitrary measure of ‘value’), addressing multiple objectives may be best evaluated by adding, multiplying, or otherwise combining utilities in what is called a utility function. A simple utility function for two attributes might be:

$U(x_1, x_2) = w_1u_1(x_1) + w_2u_2(x_2) + w_3u_1(x_1)u_2(x_2)$

where

U= utility of a set of attributes

u= utility associated with a particular attribute x

w= scaling weights assigned to address tradeoffs

Utility functions also incorporate risk aversion. In the case of adverse events, most individuals either have a risk-neutral aversion curve (i.e., as risk increases, aversion increases in the same fashion), or a curve that represents exponentially increasing risk aversion as risk increases in a linear fashion. People also tend to be more averse to risks that are ‘strange’, uncertain, or otherwise out of the range of normal experience. Arguably, NEOs may fall into this category: the concept of an object from space causing considerable damage is far removed from many individuals’ sphere of thinking. Recent media coverage of the Chelyabinsk event and the NEO hazard may be changing this. It is critical to capture risk aversion in a decision analysis, as it can have a large impact on the utility function and ranking of alternatives.

Time preference is another important factor. A wealth of research demonstrates that most people ‘devalue’ risks, costs, and benefits that occur in the distant future as opposed to the near-term. Many people have a difficult time conceptualizing the benefit of money spent today on risk management for NEOs that may not approach the Earth for decades. In economic terms, people are often (but not always) less willing to pay for managing future risks as opposed to today’s risks. This willingness-to-pay can be characterized by careful surveys, and is often represented by a discount rate. As discount rates may vary widely among different decision participants, and have an exponential influence in decision calculations, careful definition is crucial.

The outcome of a decision analysis can be modeled in a number of ways. For the NEO issue, it is likely that there will be multiple objectives, and thus some measure of multi-objective (or attribute) utility would be used for ranking of alternatives. Resources that are potentially expended or lost are of particular interest. For example, if one international agency had a designated budget for NEO study and risk management, then the problem may be structured as one of cost-effectiveness; i.e. what is the alternative that results in the greatest benefit for the least cost? However, because multiple agencies and governments are likely to be involved, a net benefit (e.g., benefits minus costs) decision analysis is probably more meaningful.

2.5 *Sensitivity Analysis*

The result of a decision analysis model, incorporating multiple objectives and a set of alternatives, is a ranking of the alternatives based on how well they satisfy the objectives. The ranking is based upon the expected value of each alternative. However, as there are multiple sources of uncertainty in such decisions, it is important to determine the impact that uncertainties have upon the ranking, and which variables contribute most to overall uncertainty.

The simplest means of conducting sensitivity analysis is to vary the values of each model variable one at a time, and determine the impact (if any) upon the ranking of alternatives. If changing the values of a variable does not affect the ranking, then the results are insensitive to that variable. This can be done with combinations of variables as well. However, it is much more efficient to conduct sensitivity analysis on all variables simultaneously in a simulation environment (e.g., Monte Carlo simulation), and then determine sensitivity via rank correlation, response surface methods, or other means [9]. The result of such a sensitivity analysis is a ranking of variables in terms of the degree to which they influence the ranking of alternatives in the decision analysis. This provides valuable information to decision participants, because the variables that influence the results the most are those that are the most uncertain, indicating which variables require additional or better quality information.

An associated type of analysis is ‘value-of-information’ analysis [9], in which the actual resource implications of information collection can be estimated; e.g., what amount of money should be spent in uncertainty reduction? This is accomplished via Bayesian calculations that start with ‘prior’ uncertainties, and then ‘update’ these uncertainties with additional information. If the additional information reduces the prior uncertainty associated with a particular variable to a great degree, then it may be worth expending more resources on refining that variable. For example, NEO search and characterization experts agree that more sensitive searches and more extensive characterization are ‘better’ because we have detailed physical information for only a few objects. However, the benefit from expending considerable resources on better searches and/or characterization has not been estimated in terms of how this may influence deflection or other decisions. As space-based observation or reconnaissance is likely to be costly, such a value-of-information analysis would be worthwhile.

2.6 *Temporal and Spatial Issues*

The NEO decision-making landscape is constantly shifting; new information is becoming available, new technologies being developed, and so on. Thus, a decision analysis framework for NEO risk management ideally should be dynamic. The simplest way to do this is to run the decision model in an iterative fashion periodically so that information can be updated. A more efficient alternative may be to structure the decision model within a dynamic modeling construct, using a method such as system dynamics [10]. This would make the decision analysis more complex, but an additional strength of system dynamic modeling is the ability to model complex networks (such as power grids) and unanticipated consequences of particular actions. Such modeling is also able to inform strategies that increase resilience of systems to damage.

It would be informative if the spatial issues associated with a potential NEO impact were assessed. For example, an alternative that reduced the risk of a NEO impacting a populated area versus a remote land area or the ocean could be visualized via geographic information systems, or GIS.

2.7 *Choosing an Alternative Strategy*

As Figure 1 represents, the choice of an alternative can be deferred if the sensitivity/value-of-information analysis indicates that further information collection is warranted (e.g., in a case where decision participants are uncomfortable with the existing level of uncertainty). At some point, however, a decision must be made. The decision analysis model does not make decisions- people make decisions. In any decision-making structure, clear decision-making authority and responsibility must be defined. The decision support tool would provide a level of transparency and defensibility very useful to decision-makers. Additionally, it is crucial that the decision framework and tool are embedded within a sustainable administrative structure that reduces the risk that decisions are made in a ‘one-off’ fashion, or that the framework and tool are abandoned with changes in administration or government. NEO risk management is a long-term process.

After the decision is made, a different set of decision support tools may be utilized. For example, a deflection mission may be informed by optimization modeling [6]. This type of modeling can inform design of the mission, considering multiple constraints such as time, resources, technological aspects, and so on. Ideally, the outcomes and resource utilization associated with the decision should be tracked to determine indeed whether the ‘right’ decision was made. To improve response to future NEO events and appropriate resource allocation, a NEO risk management program evaluation process should be followed.

3.0 Calculation

The types of modeling described here can be combined via custom computer programming, or via use of a number of commercial programs, into a user-friendly decision support tool. The most inclusive and informative type of model represented here would integrate Bayesian decision analysis calculations into a system dynamics model that is linked with GIS. Such a model could be made user-friendly by using graphical means. It should be hierarchical, with the ability for users to ‘drill down’ to whatever level is necessary for use (eventually down to raw data). In any case, a Web-based platform would be most useful in order to allow multiple decision participants worldwide to use the decision support tool simultaneously. Linkage to a database of NEO characteristics, projected orbits, etc. would facilitate rapid updating.

4.0 Results, Discussion, and Conclusions

A decision analysis framework is presented for informing decisions regard NEO risk management. The sequential components of the framework are described, and a proposed model structure is presented. The results of such a framework will guide development of a decision support tool that can be used by any decision participant. A sustainable decision-making structure that employs analysis should be crafted so that it is resilient to organizational/political changes. This is a common problem in many organizations; when the management or organization itself changes, the need for analysis may change. Indeed, a properly designed decision support approach and tools that are ‘embedded’ in an organization can prompt organizational improvement and learning.

Decisions can, of course, be made without employing such a tool, but history has demonstrated many times that *not* using such a tool to inform such a complex decision is likely to result in failure, wasted resources, and associated controversy. Recent natural and man-made disasters such as Hurricane Katrina and the destruction of the World Trade Center in the US are prominent examples.

5.0 References

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Vitae

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