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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 and 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 are 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.

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 is the science of informing difficult decisions. 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.

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 (defined here as "decision participants"). The basic problem here can be framed as: "What is the best strategy to manage risk associated with NEOs?" Some high-level objectives might be to minimize: mortality and injuries, damage to critical infrastructure (e.g., power, communications and 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.

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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 and 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.

1. 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 a form of quantitative risk management analysis called 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 (Fig. 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