Near-Earth object hazardous impact: A Multi-Criteria Decision Making approach.

J. M. Sánchez-Lozano[1], M. Fernández-Martínez[2] and J.M. Trigo Rodríguez[3]
[1]University Centre of Defence at the Spanish Air Force Academy, MDE-UPCT. C/Coronel López Peña, s/n. 30720. Santiago de la Ribera, Murcia, Spain, juanmi.sanchez@cud.upct.es
[2]University Centre of Defence at the Spanish Air Force Academy, MDE-UPCT. C/Coronel López Peña, s/n. 30720. Santiago de la Ribera, Murcia, Spain, manuel.fernandez-martinez@cud.upct.es
[3]Institute of Space Sciences (IEEC-CSIC), Campus UAB, Carrer de Can Magrans s/n, 08193 Cerdanyola del Vallés (Barcelona), Spain. trigo@ice.csic.es

Introduction: Near-Earth asteroids, described as rocky bodies with sizes ranging from one meter to few kilometers in diameter, may constitute a potential threat when approaching our planet. While most of them might impact the Earth in the next million years with a probability close to 0.5% [1], there is a chance of approximately 1% that an impact > 1000 MT (equivalent to 100 Tunguskas) might happen once each century [2]. Several estimations to quantify the frequency of hazardous Near-Earth objects (NEOs) impacting our planet have been contributed in the scientific literature [3-4]. Among them are the Torino scale [5] and the Palermo scale [6]. Several factors, including impact energy, impact velocity, estimated diameter, number of potential impacts, absolute magnitude, and impact probability, are also used to quantify the risk of NEO impacts [6]. As such, it is clear that an assessment of hazardous NEOs involves a wide list of varied nature criteria. In this communication, we describe the first known Multi-Criteria Decision Making (MCDM) approach for hazardous NEO assessment. More specifically, we applied Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) to classify hazardous NEOs. A MCDM problem consists of a set of alternatives to be evaluated with respect to a list of criteria. All that information is contained in a decision matrix. The main goal is to find the best option among all the alternatives once they have been assessed by the decision criteria.

Structure of the decision problem: In this communication, Any image file format that can be imported into we provide a novel scale for assessing hazardous NEOs according to several measures provided by NASA Near Earth Object Program [7]. Both AHP [8] and TOPSIS [9] approaches were applied. All of the potential future Earth impact events are listed therein once JPL Sentry System detects them based on currently available observations. For calculation purposes, we collected the 101 larger NEOs (with estimated diameters > 50 m) listed in Sentry Risk Table on March 16, 2016. These NEOs constitute the alternatives of our MCDM approach.

Decision criteria to assess hazardous NEOs: **C_1: Potential impacts**. The number of dynamically distinct potential impacts detected by Sentry System. This criterion must be maximized.

C_2: Impact Probability (cumulative). The sum of the impact probabilities from all detected potential impacts. This attribute should be maximized.

C_3: $V_{infinity}$ (km/s). The relative velocity at atmospheric entry of the asteroid relative to the Earth, which assumes a massless Earth and disregards the acceleration caused by Earth's gravitational field. This criterion must be maximized.

C_4: H (Absolute Magnitude). This measures the intrinsic brightness of the object. This attribute should be minimized.

C_5: Estimated Diameter (km). The estimated diameter of the asteroid, calculated under the assumption of a uniform spherical body with a visual albedo equal to 0.154. This criterion must be maximized.

C_6: Palermo Scale (cumulative). The cumulative rating of the hazard according to the Palermo Technical Impact Hazard Scale [6]. This attribute must be maximized.

C_7: Energy (Megatons of TNT). The kinetic energy at impact. This value is based on the absolute magnitude (C_4) and impact velocity of each asteroid. This criterion should be maximized.

A hazardous NEO assessment problem can be understood with a two level hierarchical structure. As such, our goal is to find the most hazardous NEO (A_i, $i=1,\dots,n \geq 2$) with respect to the decision criteria (C_j, $j=1,\dots,m \geq 2$) and the experts' knowledge (E_k, $k=1,\dots,r \geq 2$). Based on the assumptions of TOPSIS approach, the decision criteria may not be equally important by default.

Determining the criteria weights: To determine the weights of the criteria, a group of NASA experts was required to answer a 3-question survey [10]. Thus, a pairwise comparison among the criteria was conducted to determine the criteria weights. The most relevant criterion was found to be C_6. Such a criterion is used by NASA to rank the NEOs in the Sentry Risk Tables of Near Earth Object Program [7]. The next criteria (sorted by weight in descending importance) were found to be C_1 and C_2. In contrast, the least important criteria were C_4 (H magnitude) and C_5 (estimated diameter).

Evaluating hazardous NEOs: TOPSIS approach was used to determine the order of preference among all the alternatives. That algorithm is especially appropriate for the assessments of alternatives (on the basis of a set of criteria) that are not displayed in the same units. Our MCDM approach to assess hazardous NEOs arranges all the information in a decision matrix consisting of 101 rows by 7 columns. Once the TOPSIS approach was applied, a coefficient R_i for each alternative was obtained according to their relative closeness to the ideal solution. As such, all the NEOs considered in this study were ranked according to TOPSIS approach (c.f. [10]).

According to our TOPSIS based ranking, the two most hazardous NEOs were found to be 410777 (2009 FD) and 2011 SR52. Their TOPSIS scores were the highest, much higher than the remaining objects. Observe that the 1st ranked NEO, 410777 (2009 FD), has a low number of potential impacts (C_1) and low impact energy (C_7). However, it presents a high value on the (cumulative) Palermo scale (C_6) and also the highest (cumulative) impact probability (C_2). Likewise, according to our TOPSIS score, the 2nd ranked NEO (2011 SR52) only presents a few potential impacts, it has assigned a low impact probability, and an intermediate score on the Palermo scale (cumulative). Also, 2011 SR52 is the NEO with the highest impact energy. probability (C_2), absolute magnitude (C_4), and estimated diameter (C_5).

Sensitivity analysis: This additional analysis allows to verify the validity of the TOPSIS algorithm results. Thus, the sensitivity analysis involved all the 101 NEOs under the assumption that all the criteria are equally weighted. As a result, only slight differences among the 10 top-rated objects were found. In fact, 8 objects still appeared among the 10 most hazardous NEOs (410777 (2009 FD), 2011 SR52, 2015 HV182, 2010 MA113, 2014 NZ64, 2008 VS4, 101955 Bennu (1999 RQ36) and 29075 (1950 DA)) . Additionally, according to the new TOPSIS ranking, the two first-rated and most hazardous NEOs (410777 (2009 FD) and 2011 SR52) were exactly the same as provided by the previous TOPSIS approach. Only their positions were interchanged. This new approach allowed the authors to dismiss a possible bias regarding the experts' knowledge. These results suggest that the judgments provided by the experts do not greatly influence the criteria weights, and hence, our TOPSIS based ranking for hazardous NEO assessment.

Conclusions: The first-known MCDM based approach for rating hazardous NEOs has been presented in this short communication. First, we applied AHP to determine the weight of each criterion involved in this study. With this aim, a group of NASA experts was surveyed. The most relevant criterion was found to be (cumulative) Palermo scale. This attribute matches the sort order used by Sentry Risk Tables in the NASA Impact Risk Section (c.f. Near Earth Object Program [7]). A TOPSIS approach was conducted to rate all the involved alternatives, i.e., the 101 most hazardous NEOs (with diameters > 50 m) according to NASA Near Earth Object Program. As a result, the two most hazardous objects were found to be 410777 (2009 FD) and 2011 SR52. A sensitivity analysis was also developed to assess whether the experts' judgments influenced our TOPSIS ranking from a subjective viewpoint and concluded that there was no significant bias. Moreover, our contributed TOPSIS ranking for hazardous NEOs does not substantially vary whenever all the criteria are considered to be equally relevant. We would like to point out that this study was carried out according to some of the most relevant NEO features identified by NASA Near Earth Object Program to assess the hazardous level of such objects. Also, the 101 NEOs involved in our study have been tagged as the most hazardous objects by NASA Sentry [7].

Some drawbacks concerning the present study are stated next. First, our TOPSIS based approach for hazardous NEOs assessment involves several MCDM techniques that should be introduced to astronomers skilled in NEOs. As mentioned above, MCDM techniques have been widely applied in other scientific fields, though their application to NEO classification is new. Because of this novelty, an understanding of their mathematical foundations is necessary. It is also worth noting that our TOPSIS ranking for hazardous NEOs is focused on larger objects [11].

References:

[1] Rabinowitz, D. et al. (2000) *Nature*, 403, 165-166. [2] Chapman, C. R. and Morrison, D. (1994) *Nature* 367, 33-40. [3] Sidle, R. C. (2007) *In Comet/Asteroid Impacts and Human Society. An Interdisciplinary Approach*, 383-398. [4] Brown P. et al. (2013) *Nature* 503, 238-241 [5] Fulchignoni, M. and Barucci, M. A. (2005) *Comptes Rendus Phys*., 6, 283-289. [6] Chesley, S. R. et al. (2002) *Icarus*, 159, 423-432. [7] Chodas, P. and Baalke, R. Sentry Risk Table at NASA Near Earth Object Program (Impact Risk): http://neo.jpl.nasa.gov/risk/ [accessed 03.17.16]. [8] Saaty, T. L. (1980) The Analytic Hierarchy Process. [9] Hwang, C. L. and Yoon, K. (1981) *Multiple Attribute Decision Methods and Applications*. [10] Sánchez-Lozano, J. M. and Fernández-Martínez, M. (2016) *Scientific Rep*., 6, Art. No.: 37055. [11] Perna, D. et al. (2013) *The Astronomy and Astrophysics Review*, 21–65.