SCIENTIFIC REPORTS

OPEN

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

J. M. Sánchez-Lozano & M. Fernández-Martínez

Received: 01 July 2016

Accepted: 24 October 2016

Published: 16 November 2016

The impact of a near-Earth object (NEO) may release large amounts of energy and cause serious damage. Several NEO hazard studies conducted over the past few years provide forecasts, impact probabilities and assessment ratings, such as the Torino and Palermo scales. These high-risk NEO assessments involve several criteria, including impact energy, mass, and absolute magnitude. The main objective of this paper is to provide the first Multi-Criteria Decision Making (MCDM) approach to classify hazardous NEOs. Our approach applies a combination of two methods from a widely utilized decision making theory. Specifically, the Analytic Hierarchy Process (AHP) methodology is employed to determine the criteria weights, which influence the decision making, and the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) is used to obtain a ranking of alternatives (potentially hazardous NEOs). In addition, NEO datasets provided by the NASA Near-Earth Object Program are utilized. This approach allows the classification of NEOs by descending order of their TOPSIS ratio, a single quantity that contains all of the relevant information for each object.

Asteroids, described as small rocky bodies with sizes consisting of a few metres to a few hundred kilometres in diameter, constitute a potential threat. 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 century². Hence, several studies have explored the implications of large asteroid impacts on early Earth ecosystems^{3,4}.

It turns out that the determination of the statistical frequency of an asteroid impact is less relevant than stating whether an asteroid may impact the Earth⁵. Even small objects (with diameters ranging from 50 to 100 m) may cause great damage. In fact, these types of small objects may lead to so-called Tunguska-class events whose impact energy is equivalent to 10 MT of TNT⁶.

Near-Earth objects (NEOs) are small asteroids that orbit close to the Earth's orbit. NEO research provides information concerning the evolution of the early solar system⁷. Several measures to rate hazardous NEOs have been contributed in the scientific literature⁸. Among them are the Torino scale⁹, which evaluates the a priori risk due to a potentially hazardous asteroid, and the Palermo scale¹⁰, which takes into account the energy at impact and the estimated probability of the event (that might happen in a time period spanning from present time to predicted impact) with respect to a record of events with a comparable or greater level¹¹. 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 impacts¹⁰. Furthermore, other non-physical factors such as Purgatorio Ratio (PR) have been used to manage the communication of impact threats; in this case, the PR is expressed by the ratio of time between the first and last observation to the time between the present and next possible impact date¹². Therefore, it is clear that an assessment of hazardous NEOs involves a wide list of varied nature criteria. The impact hazard assessment requires the development of ad hoc techniques beyond what is routinely conducted by automatic impact monitoring systems¹³. In this paper, we contribute the first known Multi-Criteria Decision Making (MCDM) approach for hazardous NEO assessment. More specifically, we have applied the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) to classify hazardous NEOs.

Next, we will motivate the application of MCDM techniques to hazardous NEO assessment. 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

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. Correspondence and requests for materials should be addressed to J.M.S.-L. (email: [juanmi.sanchez@cud.upct.es](mailto:juanmi.sanchez@ cud.upct.es)) or M.F.-M. (email: manuel.fernandez-martinez@cud.upct.es)

been assessed by the decision criteria. Sometimes, it is not possible to find a solution that satisfies all the criteria simultaneously¹⁴. In these cases, the Multiple Criteria Decision Analysis (MCDA) plays a key role since it allows the decision makers to properly tackle the decision making process. In addition, the MCDA involves a wide range of techniques to systematically address each decision problem. These techniques also facilitate a consensus regarding the final decision and the treatment of a large amount of information, which is usually expressed by various measurement magnitudes and meanings.

Over the years, several MCDM techniques have been developed in the scientific literature. Each MCDM approach uses distinct paradigms and concepts. Among them, we can cite ELimination Et Choix Traduisant la REalité (Elimination and Choice Expressing Reality, ELECTRE)¹⁵; Analytic Hierarchy Process (AHP)¹⁶; TOPSIS¹⁷; Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)¹⁸; Ordered Weighted Averaging (OWA)¹⁹; Analytic Network Process (ANP)²⁰ and ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)²¹. Most of these approaches were introduced during the late nineties, though because of their great usefulness, they are still applied in several areas of engineering such as energy, materials, safety and risk management, operations research and soft computing and information technology management²². However, to the best of our knowledge, these techniques have not been previously applied to astronomy and thus constitute the innovation of the present study. In fact, the present study represents the first-known application of MCDM techniques to NEO hazard assessment.

The decision problem: near-Earth object (NEO) hazardous impact

Structure of the decision problem. In this paper, we provide a novel scale for assessing hazardous NEOs according to several measures provided by the NASA Near Earth Object Program²³. We have applied MCDM techniques, including both AHP and TOPSIS approaches, as described in the Methods section. Our main data source consists of the Sentry Risk Table available from the National Aeronautics and Space Administration (NASA) Near Earth Object Program (c.f. Impact Risk Section)²³. All of the potential future Earth impact events are listed therein once the JPL Sentry System has detected them based on currently available observations. The Sentry System is a highly automated collision monitoring system that continually scans the most current asteroid records and reports the possibility of future Earth impacts over the next 100 years²³.

Note that all the objects appeared in both tables, namely, both recently observed objects (within past 60 days) and not recently observed objects are sorted in descending order by the Palermo Scale (cumulative). For calculation purposes, we have collected the 101 larger NEOs listed in the Sentry Risk Table on March 16, 2016. These NEOs, which constitute the alternatives of our MCDM approach, were selected as being non-small, i.e., with an estimated diameter >50 m. In terms of the Torino Scale, all the objects in the Sentry Risk Table were highlighted in a colour other than white. Thus, following a decreasing Palermo Scale (cumulative) sort order criterion, it follows that the top rated NEOs are 29075 (1950 DA), 101955 Bennu (1999 RQ36), 410777 (2009 FD), 1979 XB, and 99942 Apophis (2004 MN4), as shown on the NASA Near Earth Object Program (Impact Risk) website²³. The calculations via the MCDM techniques were conducted one day later, on March 17, 2016. This date was taken into account for calculations involving the PR.

Next, we describe the decision criteria involved in the present study. These criteria allow us to calculate a single quantity for each of the 101 potentially hazardous NEOs (alternatives) for classification purposes.

Decision criteria (C_i) to assess hazardous NEOs. Our main goal is to assess and classify the potentially most hazardous NEOs. Next, we provide a description regarding all the decision criteria we have selected to undertake this task.

- **C_1 : Potential Impacts.** The number of dynamically distinct potential impacts detected by the Sentry System. There can be several qualitatively unique pathways that describe an impact in a given year. For example, the pathways can include those having extra revolutions around the Sun or those deflected by an earlier planetary encounter. This criterion must be maximized.
- **C_2 : Impact Probability (cumulative).** The sum of the impact probabilities from all detected potential impacts. For each potential impact, the corresponding impact probability represents the probability that each tabulated impact will occur. The calculations involving these probabilities are quite complex. This attribute should be maximized.
- **C_3 : V_{∞} (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 the Earth's gravitational field. This quantity is often called the *hyperbolic excess velocity* and is calculated through the expression $V_{\infty}^2 = V_{\text{impact}}^2 - V_{\text{escape}}^2$, where the Earth's escape velocity is approximately equal to 11.2 km/s. This criterion must be maximized.
- **C_4 : H (Absolute Magnitude).** This is a measure of the intrinsic brightness of the object. Specifically, it is the apparent magnitude of the object at 1 Astronomical Unit (AU, $\sim 1.4960 \cdot 10^{11}$ m) from both the Sun and the observer and at a full phase. This attribute should be minimized.
- **C_5 : Estimated Diameter (km).** The estimated diameter of the asteroid and is calculated under the assumption of a uniform spherical body with a visual albedo equal to 0.154; however, sometimes it is estimated through actual measured values (if available). Nevertheless, since the albedo is rarely known for the objects involved in this study, the diameter estimate is approximate. In most cases, this measure will be accurate to within a factor of two. This criterion must be maximized.
- **C_6 : Palermo Scale (cumulative).** The cumulative rating of the hazard according to the *Palermo Technical Impact Hazard Scale*¹⁰. This attribute for the NEOs 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. The estimation follows the guidelines established by the Palermo Technical Scale and is calculated through the expression $0.5 \cdot \text{Mass} \cdot V_{\text{impact}}^2$. The uncertainty in this value is mainly due to the uncertainty in the asteroid mass. Thus, the kinetic energy at impact will generally be accurate to within a factor of three. This criterion should be maximized.

Figure 1. The scheme above represents the hierarchical structure concerning the assessment of hazardous NEOs. The upper node contains the main goal of this paper. Next, the two level MCDM approach is depicted. Specifically, level 1 of the hierarchy contains all the decision criteria, namely, all the NEO features we have considered for classification purposes. The second hierarchical level displays all the alternatives selected to carry out the present study, namely, all the (larger) potentially hazardous NEOs.

Labels	Verbal judgments of preferences between i and j criteria	Saaty's scale
(EI)	C_i and C_j are equally important	1
(S + I)	C_i is slightly more important than C_j	3-1/3
(St + I)	C_i is strongly more important than C_j	5-1/5
(VSt + I)	C_i is very strongly more important than C_j	7-1/7
(Ex + I)	C_i is extremely more important than C_j	9-1/9

Table 1. Scale of valuation in the pairwise comparison process. This scale is used in AHP methodology to carry out comparisons between pairs of criteria lying in the same level of a hierarchy.

According to the *Summary Table Description* provided for each NEO in NASA Impact Risk Tables, certain parameter values depend on each specific impact event and they seldom change among the different entries. For this reason, only the mean values for the C_3 , C_4 , C_5 and C_7 parameters are tabulated.

A hazardous NEO assessment problem can be understood with a two level, hierarchical structure (c.f. Fig. 1). Consequently, a classifying task for hazardous NEOs becomes a MCDM problem^{14,17}. Thus, our main goal is to find the best alternative (in this case, the most hazardous NEO) (A_i , $i = 1, \dots, n \geq 2$) regarding all of the decision criteria (C_j , $j = 1, \dots, m \geq 2$) and the experts' knowledge (E_k , $k = 1, \dots, r \geq 2$). The parameters n , r , and m are finite numbers.

On the other hand, based on the assumptions of the TOPSIS approach (Methods section), the decision criteria may not be equally important by default. This is the reason a group of four NEO experts from NASA were tasked with determining the relative weights of the evaluation criteria.

Determining the criteria weights. To determine the weights of the criteria, the group of NASA experts were required to answer a 3-question survey reproduced as follows.

Q1: Do you think that all the decision criteria as described above are equally important to assess and determine which NEOs are most hazardous in the hypothetical case of a potential impact on Earth?

In the affirmative case, it holds that $c_i = c_j = 1/n$ for all i and j . Hence, there is no further action required by experts, since all the criteria weights are the same. However, if there is one expert who believes that all the criteria are not equally relevant, then the following questions must be addressed.

Q2: List the criteria in order of descending importance.

Q3: Compare those decision criteria (C_i) chosen to be in 1st place with those placed in 2nd and so on. The following labels, which correspond to the scale of valuation in the pairwise comparison process, should be used: {(EI), (S + I), (St + I), (VSt + I), (Ex + I)} (c.f. Table 1).

Thus, a pairwise comparison among the criteria was conducted to determine the criteria weights. Then, the criteria weights provided by the experts were unified in the last stage of the alternative assessment. With this aim, a homogeneous aggregation (assuming that the knowledge of each expert is equally relevant across the whole decision process) through arithmetic averaging was completed. Table 2 contains the weights and the rank of each criterion.

Accordingly, the most relevant criterion is C_6 (cumulative Palermo scale). Interestingly, this criterion has been used by NASA to rank the NEOs in the Sentry Risk Tables²³ of the Near Earth Object Program. This fact highlights the consistency of the information provided by the experts. The next criteria (sorted by weight in descending importance) were found to be C_1 (potential impacts) and C_2 (cumulative impact probability). In contrast, the least important criteria were C_4 (H magnitude) and C_5 (estimated diameter).

Criteria	Importance weight (%)	Rank
C_1	21.2	2
C_2	20.2	3
C_3	6.6	5
C_4	5.3	7
C_5	5.8	6
C_6	23.1	1
C_7	17.8	4

Table 2. Criteria weights to assess hazardous NEOs through an experts' homogeneous aggregation via arithmetic average.

Figure 2. The figure above illustrates the concepts of PIS and NIS in a TOPSIS approach. The optimal alternative is the closest from the PIS (denoted by C) and the farthest from the NIS (located at both B and D points). TOPSIS takes into account the distances to both the PIS and the NIS simultaneously.

In addition, using an AHP approach to determine the criteria weights, a consistency analysis of the information provided by experts was conducted. Thus, the consistency ratio was computed by each expert. In all the cases, the consistency ratio measured < 0.1 (c.f. Methods section). As a result, we can guarantee the consistency of the applied method to calculate the weights of the criteria, and it was not necessary to revise the judgements provided by the experts.

Evaluating hazardous NEOs. Results and discussion. Once the criteria set had been selected and their weights quantified, the next step was to provide a measure of the effect caused by each alternative (hazardous NEO) with respect to each criterion. Hence, the TOPSIS approach was used to determine the order of preference among all the alternatives, i.e., the potentially hazardous NEOs with an estimated diameter > 50 m. Recall that this algorithm is especially appropriate for the assessments of alternatives (on the basis of the criteria) that are not displayed in the same units, as is the case in this study. Each criterion is measured in different units.

Our MCDM approach to assess hazardous NEOs displays all the information in a decision matrix consisting of 101 rows (all the NEOs involved in this study) by 7 columns (all the decision criteria, C_i). In fact, all the entries of the matrix are quantities provided by the Sentry Impact Risk tables from the NASA Near Earth Object Program²³.

Once the TOPSIS approach was applied, a coefficient (R_i) for each alternative was obtained according to their relative closeness to the ideal solution (c.f. Fig. 2). Thus, all the NEOs considered in this study have been ranked according to TOPSIS approach. A selection of the 10 most hazardous NEOs ranked in descending order is provided in Table 3. Additionally, Appendix A contains the entire TOPSIS ranking, which includes the 101 NEOs considered in this study.

According to our TOPSIS based ranking, the two most hazardous NEOs are 410777 (2009 FD) and 2011 SR52. These NEOs have the highest TOPSIS scores, which are much higher than the remaining NEOs. The information provided in Table 4 supports the TOPSIS methodology of a continuous balance of either the excess or deficiency in the criteria values. To illustrate this, the 1st ranked NEO 410777 (2009 FD) is considered. The information provided by the Sentry System reveals that this NEO has a low number of potential impacts (criterion C_1) and low impact energy (C_7). However, it presents a high value on the (cumulative) Palermo scale (C_6) and also presents the highest (cumulative) impact probability (C_2). Likewise, according to the TOPSIS score, the 2nd ranked

Alternatives	R_i (TOPSIS)	Ranking	Year 1 st hypothetical impact
410777 (2009 FD)	0.4857	1	2185
2011 SR52	0.4410	2	2034
2015 HV182	0.2963	3	2016
2010 MA113	0.2786	4	2033
2014 NZ64	0.2432	5	2017
2008 VS4	0.1996	6	2016
101955 Benu (1999 RQ36)	0.1870	7	2175
2014 MO68	0.1781	8	2017
2007 KO4	0.1731	9	2022
29075 (1950 DA)	0.1510	10	2880

Table 3. Top 10 most hazardous NEOs according to TOPSIS ranking.

Alternatives	Criteria						
	C_1	C_2	C_3	C_4	C_5	C_6	C_7
410777 (2009 FD)	7	1.60E-03	15.87	22.10	0.160	−1.78	1.40E+02
2011 SR52	4	7.60E-10	13.55	15.60	0.054	−4.35	8.60E+05
2015 HV182	511	7.10E-07	7.82	21.70	0.154	−4.07	1.20E+02
2010 MA113	469	5.20E-06	3.06	23.40	0.078	−4.47	2.00E+01
2014 NZ64	388	2.10E-06	6.61	22.50	0.108	−4.25	3.20E+01
2008 VS4	304	6.20E-07	8.15	24.10	0.050	−5.25	5.00E+00
101955 Benu (1999 RQ36)	78	3.70E-04	5.99	20.20	0.490	−1.71	1.20E+03
2014 MO68	262	1.50E-06	8.36	23.50	0.067	−5.06	1.00E+01
2007 KO4	248	4.20E-06	13.71	23.30	0.075	−4.43	2.10E+01
29075 (1950 DA)	1	1.20E-04	14.10	17.60	1.300	−1.42	7.50E+04

Table 4. Decision matrix involving the 10 Top-ranked NEOs.

NEO (2011 SR52) presents only a few potential impacts, has been assigned a low impact probability, and has an intermediate score on the Palermo scale (cumulative). However, 2011 SR52 is the NEO with the highest impact energy. The case of NEO 99942 Apophis (2004 MN4) is quite interesting. This NEO gained a certain notoriety several years ago since it was the first known NEO to reach level 2 in the Torino scale⁷. However, it has been ranked in 19th position by the TOPSIS approach. This is mainly because none of its criteria values are sufficiently relevant. In fact, this NEO presents intermediate values for the most relevant criteria. Furthermore, according to our TOPSIS ranking, the potentially hazardous NEO (101955) 1999 RQ36 in the 7th position has a possibility of colliding with the Earth in the latter half of the 22nd century²⁴ and is the primary target of NASA's Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) sample return mission^{25,26}. It has been ranked 7th in the TOPSIS scale for hazardous NEOs since it presents high values for the two most relevant criteria according to the experts, namely, C_6 (cumulative Palermo scale) and C_1 (number of potential impacts). Moreover, this object also presents high values for intermediate criteria, including cumulative impact probability (C_2), absolute magnitude (C_4) and estimated diameter (C_5). Finally, we would like to discuss the specific case concerning object (29075) 1950 DA. The impact prediction horizon for this NEO is four times longer than any other asteroid²⁷. In fact, the orbit of this object is very precisely known, which allows the possibility to explore centuries in the future, much further than is usually possible (c.f. NASA Near Earth Object website). It is worth noting that (29075) 1950 DA presents the highest values concerning criteria C_6 (cumulative Palermo scale) and C_5 (estimated diameter). However, NASA reports only one unique potential impact (criterion C_1), which moves it to the 10th position in TOPSIS ranking.

Sensitivity analysis

Variation of weights. A sensitivity analysis to verify and analyse the validity of the results shown by the TOPSIS algorithm has been conducted. First, we have performed an additional analysis of all the alternatives, i.e., the 101 NEOs considered in our study, but this time under the assumption that all the criteria are equally weighted (equally relevant). Table 5 contains the 10 top-rated hazardous NEOs according to the new TOPSIS ranking.

Although the ranking order does not exactly match the ranking order provided in Table 3, there are only slight differences among the 10 top-rated objects. In fact, under the assumption that all the criteria are equally important, 8 objects still remain among the 10 most hazardous NEOs. Additionally, according to the new TOPSIS ranking, the two first-rated and most hazardous NEOs (410777 (2009 FD) and 2011 SR52) are exactly the same as provided by the previous TOPSIS approach. Only their positions are interchanged. This new approach has allowed the authors to dismiss a possible bias underlying the experts' knowledge; however, a consistency ratio was

Alternatives	Weights through experts group (Table 2)		All the criteria with the same weight	
	R_i (TOPSIS)	Ranking	R_i (TOPSIS)	Ranking
410777 (2009 FD)	0.4857	1	0.4479	2
2011 SR52	0.4410	2	0.4526	1
2015 HV182	0.2963	3	0.2646	4
2010 MA113	0.2786	4	0.2459	5
2014 NZ64	0.2432	5	0.2144	6
2008 VS4	0.1996	6	0.1748	10
101955 Bennu (1999 RQ36)	0.1870	7	0.1903	7
2014 MO68	0.1781	8	0.1558	12
2007 KO4	0.1731	9	0.1538	13
29075 (1950 DA)	0.1510	10	0.2732	3

Table 5. Top-rated alternatives by TOPSIS provided that all the criteria are chosen to be equally relevant.

Alternatives	Assigning PR 25% of the overall relevance and remaining criteria being equally weighted		Weights provided by experts (c.f. Table 2)	
	R_i (TOPSIS)	Ranking	R_i (TOPSIS)	Ranking
2013 NH6	0.5882	1	0.0452	71
410777 (2009 FD)	0.2881	2	0.4857	1
2011 SR52	0.2829	3	0.4410	2
99942 Apophis (2004 MN4)	0.2225	4	0.0867	19
29075 (1950 DA)	0.1860	5	0.1510	10
2015 HV182	0.1660	6	0.2963	3
2010 MA113	0.1530	7	0.2786	4
101955 Bennu (1999 RQ36)	0.1398	8	0.1870	7
2014 NZ64	0.1318	9	0.2432	5
2005 GV190	0.1082	10	0.0705	31

Table 6. Comparing the top-rated alternatives including the PR (the two columns on the left) vs. excluding it. The calculations have been carried out via the TOPSIS approach in both cases.

previously estimated for this purpose. In addition, the results suggest that the judgements provided by the experts through their AHP based surveys do not greatly influence the criteria weights, and hence the TOPSIS ranking contributed to this paper for hazardous NEOs.

Involving the Purgatorio Ratio. One of the NASA experts taking part in the AHP survey suggested that the authors utilize the *Purgatorio Ratio* (PR) in the TOPSIS scale for the NEOs. When a NEO is observed during a given time window, this parameter is estimated by the ratio of the first and last observations and the time between the present and the next possible future impact date¹².

Thus, being encouraged by that interesting proposal, our next goal was to verify the effect of the PR in hazardous NEO assessment. Hence, a new column was added to our decision matrix, which included the PR values for each of the 101 most hazardous NEOs to be assessed. The PR calculations were performed on March 17, 2016 (our present time). Moreover, to determine whether the PR criterion influenced the previous TOPSIS results, we assigned this criterion a value of 25% of the overall relevance. The remaining 75% was equally assigned to the remaining criteria (C_1 – C_7). Once all the stages involved in the TOPSIS approach were carried out, a new ranking was obtained (c.f. Table 6).

A comparison of the 10 most hazardous NEOs in the TOPSIS ranking with and without the PR criterion (using the weights calculated from the experts' knowledge) indicates that only three objects are not ranked among the 10 most hazardous NEOs.

In addition, the new first and fourth objects are 2013 NH6 and 99942 Apophis (2004 MN4), respectively. This fact could be justified on the basis that both of them have been observed for a long time (more than 3000 days) and also because the closest impact date is in the far-distant future (2060). Therefore, even if the PR is given a high weight as a decision criterion, we have verified that the actual influence of this parameter in the TOPSIS ranking for hazardous NEO assessment is low.

Conclusions

In this paper, the first-known MCDM based approach for rating hazardous NEOs has been presented. The steps are summarized as follows. First, we have considered an AHP procedure to quantify the relevance or weight of each criterion involved in our study. For this task, a group of NASA experts was surveyed.

The most relevant criterion was found to be the (cumulative) Palermo scale. This criterion matches the sort order used by the Sentry Risk Tables in the NASA Impact Risk Section (c.f. Near Earth Object Program²³). A TOPSIS approach was conducted to rate all the involved alternatives, namely, the 101 most hazardous NEOs (with a diameter $>50\text{ m}$) according to the NASA Near Earth Object Program. As a result, the two most hazardous objects were found to be 410777 (2009 FD) and 2011 SR52.

Additionally, we have developed a sensitivity analysis to assess whether the experts' judgements 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 provided that all the criteria are considered to be equally relevant. This strengthens the results displayed by our MCDM procedures. Similarly, we verified that the PR is not significantly relevant and will not be included as a decision criterion in our study.

Furthermore, the present study has been carried out according to several of the most relevant NEO features identified by the NASA Near Earth Object Program (c.f. Sentry Risk Table and Earth Impact Tables – for each NEO) to assess the hazardous level for these kinds of objects. Additionally, the 101 NEOs involved in our study have been tagged as the most hazardous objects by the NASA Sentry.

Next, we discuss some of the drawbacks regarding the present study. 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, the 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 the mathematical basis becomes quite necessary. Another drawback of our TOPSIS based ranking for hazardous NEOs concerns the type of objects considered as the alternatives in our MCDM based approach. More specifically, our TOPSIS ranking for hazardous NEOs is focused on larger objects. This amounts to a total of 101 objects from a larger family⁷.

Methods

Analytic Hierarchy Process (AHP). This methodology has been accepted by the research community as a robust and flexible MCDM model to address complex decision problems¹⁶. The AHP consists of three main tasks: to structure the complex decision as a hierarchy of goals, criteria and alternatives; to conduct a pairwise comparison of all the elements in each level of the hierarchy with respect to each of the criteria involved in the previous level; and to vertically synthesize the judgements on the different levels of the hierarchy. Therefore, the AHP attempts to estimate the impact of each alternative on the overall hierarchy objective. In this paper, we have applied this methodology for only criteria weight calculation purposes. Next, we summarize how the AHP works.

Let us assume that the quantified judgements provided by the decision maker for any criteria pair (C_i, C_j) are the entries in the following n -order matrix:

$$C = \begin{matrix} & \begin{matrix} C_1 & C_2 & \cdots & C_n \end{matrix} \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} & \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{bmatrix} \end{matrix}$$

For instance, note that the input c_{12} is about the relative significance of C_1 with respect to C_2 , i.e., $c_{12} \approx (w_1/w_2)$. That idea can be further extended and hence the statements below can be expressed as follows:

1. $c_{ij} \approx (w_i/w_j)$, for all $i, j = 1, 2, \dots, n$.
2. $c_{ii} = 1$, for all $i = 1, 2, \dots, n$.
3. If $c_{ij} = \alpha \neq 0$, then $c_{ji} = 1/\alpha$, for all $i = 1, 2, \dots, n$.
4. If the criterion C_i becomes more relevant than C_j then $c_{ij} \cong (w_i/w_j) > 1$.

The abovementioned rules generate a positive and symmetric matrix (C) with its main diagonal containing ones. Accordingly, the decision maker provides value judgements to fill in an upper triangular matrix. Moreover, as the Saaty scale indicates²⁸, the values assigned to each entry c_{ij} usually lie in the interval $[1,9]$ or their reciprocals. Therefore, Table 1 contains the decision maker's linguistic preferences and a pairwise comparison process that have been considered in our hazardous NEO assessment case studies.

Thus, if n is the order of matrix C , then the number of judgements L in the corresponding upper triangular matrix is given by the following expression:

$$L = n(n - 1)/2. \quad (1)$$

On the other hand, the vector of weights is given by the eigenvector that corresponds to the maximum eigenvalue $\lambda_{\max}$ of C . The standard eigenvector method to estimate the weights in the AHP methodology measures the consistency of the referee's preferences, which were arranged in the comparison matrix. The Consistency Index (CI) is calculated by $CI = (\lambda_{\max} - n)/(n - 1)$, so if the expert shows a minor inconsistency, then $\lambda_{\max} > n$. The Saaty scale provides the next indicator for the Consistency Ratio: $CR = CI/RI$, where RI is the Random Index, which can be calculated as the average value of CI (c.f. Table 7) for random matrices^{29,30,31}. Therefore, CI is used to quantify the probability that the judgements' matrix was randomly created³² and hence the matrix is said to be consistent (in the sense of Saaty) provided that $CR < 0.1$.

TOPSIS approach. The Technique for Order Performance by Similarity to Ideal Solution, known as TOPSIS, was first introduced by Hwang & Yoon¹⁷ and is one of the classical MCDM procedures^{33,34}. This approach selects

n	1–2	3	4	5	6	7	8	9	10
RI	0.00	0.5247	0.8816	1.1086	1.2479	1.3417	1.4057	1.4499	1.4854
n	11	12	13	14	15				
RI	1.5140	1.5365	1.5551	1.5713	1.5838				

Table 7. Random Index (RI) for matrix orders from 1 to 15 where n represents the number of compared criteria³¹.

	w_1	w_2	...	w_j	...	w_n
	C_1	C_2	...	C_j	...	C_n
A_1	x_{11}	x_{12}	...	x_{1j}	...	x_{1n}
A_2	x_{21}	x_{22}	...	x_{2j}	...	x_{2n}
...	...	...	...	...	...	...
A_m	x_{m1}	x_{m2}	...	x_{mj}	...	x_{mn}

Table 8. Decision matrix for a TOPSIS approach. x_{ij} refers to the performance score of alternative A_i with respect to criteria C_j and $W = [w_1, w_2, \dots, w_n]$ denotes the weight vector associated with these criteria.

an optimal alternative that presents the shortest distance from the positive ideal solution (PIS) and the farthest distance from the negative ideal solution (NIS). Therefore, the optimal solution provided by TOPSIS constitutes a compromise solution according to the decision-maker's preferences (c.f. Fig. 2).

The following key arguments support the utilization of TOPSIS in a wide range of applications³⁵:

- TOPSIS logic is rational and understandable.
- The computation processes are straightforward.
- The concept pursues the best alternatives for each criterion from an easy mathematical viewpoint.
- The relevance weights are incorporated into the comparison procedures.

The TOPSIS approach requires several assumptions³⁶ to be verified to guarantee the proper application to a given dataset. They are as follows:

- It is assumed that all the criteria in the decision matrix take either monotonically increasing or monotonically decreasing utility. This means the larger the criterion outcomes, the greater the preference for the “benefit” criterion and a reduced preference for the “cost” criterion.
- Any outcome expressed non-numerically should be quantified throughout an appropriate scaling technique.
- By default, all the criteria cannot be assumed equally relevant. In this way, this procedure receives a set of weights from the decision maker.

Next, we provide a detailed description of each step in the TOPSIS approach.

Step 1: Establishing a performance matrix

A_i ($i = 1, \dots, m$) denotes the collection of alternatives that have to be evaluated by the series of criteria C_j ($j = 1, \dots, n$). This leads to the following decision matrix (c.f. Table 8):

Step 2: Normalizing the decision matrix

In this stage, we have obtained the corresponding normalized decision matrix. The value of each criterion is normalized by dividing it by the following (Euclidean) norm.

$$n_{ij} = x_{ij} / \sqrt{\sum_{i=1}^m x_{ij}^2}, j = 1, \dots, n \quad (2)$$

Thus, the scale becomes the same for each criterion.

Step 3: Calculating the weighted normalized decision matrix

The elements of the weighted normalized decision matrix V are calculated through the following expression:

$$v_{ij} = w_j \otimes n_{ij}, j = 1, \dots, n, i = 1, \dots, m. \quad (3)$$

where the w_j 's satisfy $1 = \sum_{j=1}^n w_j$. This provides the weight of the j th attribute, which is calculated by the AHP methodology.

Step 4: Determining the positive ideal solution (PIS) and the negative ideal solution (NIS)

Let A^+ denote the positive ideal value set, which contains the best performance scores, and let A^- be the negative ideal value set, containing the worst performance scores. Mathematically,

$$A^+ = \{v_1^+, \dots, v_n^+\} = \begin{cases} \max_i \{v_{ij}, j \in J\}: i = 1, 2, \dots, m & \text{if criterion is to maximize} \\ \text{or} \\ \min_i \{v_{ij}, j \in J'\}: i = 1, 2, \dots, m & \text{if criterion is to minimize} \end{cases}$$

$$A^- = \{v_1^-, \dots, v_n^-\} = \begin{cases} \min_i \{v_{ij}, j \in J\}: i = 1, 2, \dots, m & \text{if criterion is to maximize} \\ \text{or} \\ \max_i \{v_{ij}, j \in J'\}: i = 1, 2, \dots, m & \text{if criterion is to minimize} \end{cases} \quad (4)$$

where the index J is associated with the criteria that give profits or benefits and the index J' is associated with those ones indicating costs or losses.

Step 5: Calculating the separation measures

To estimate the separation of each alternative (PIS and NIS), the following expressions are calculated:

$$d_i^+ = \left\{ \sum_{j=1}^n (v_{ij} - v_j^+)^2 \right\}^{\frac{1}{2}}, i = 1, \dots, m \quad (5)$$

$$d_i^- = \left\{ \sum_{j=1}^n (v_{ij} - v_j^-)^2 \right\}^{\frac{1}{2}}, i = 1, \dots, m \quad (6)$$

Step 6: Calculating the relative closeness to the ideal solution

First, the ranking score R_i is calculated as follows:

$$R_i = \frac{d_i^-}{d_i^+ + d_i^-}, i = 1, \dots, m. \quad (7)$$

Thus, if $R_i = 1$, then $A_i = A^+$, whereas if $R_i = 0$, then $A_i = A^-$. Notice that all the R_i lie in the open interval $(0, 1)$. Accordingly, if the R_i values are close to 1, then the higher the priority for the i th alternative.

Step 7: Ranking the preference order

In this stage, we have sorted the best alternatives according to the ranking scores R_i in descending order. In this case, the TOPSIS approach was used to evaluate all the alternatives, i.e., the 101 NEOs involved in the present study.

References

- Rabinowitz, D., Helin E., Lawrence, K. & Pravdo, S. A reduced estimate of the number of kilometre-sized near-Earth asteroids. *Nature* **403**, 165–166 (2000).
- Chapman, C. R. & Morrison, D. Impacts on the Earth by asteroids and comets: assessing the hazard. *Nature* **367**, 33–40 (1994).
- Maher, K. A. & Stevenson, D. J. Impact frustration of the origin of life. *Nature* **331**, 612–614 (1988).
- Sleep, N. H., Zahnle, K. J., Kasting J. F. & Morowitz, H. J. Annihilation of ecosystems by large asteroid impacts on the early Earth. *Nature* **342**, 139–142 (1989).
- Chapman, C. R. & Morrison, D. No reduction in risk of a massive asteroid impact. *Nature* **421**, 473 (2003).
- Brown, P., Spalding, R. E., ReVelle, D. O., Tagliaferri, E. & Worden, S. P. The flux of small near-Earth objects colliding with the Earth. *Nature* **420**, 294–296 (2002).
- Perna, D., Barucci, M. A. & Fulchignoni. The near-Earth objects and their potential threat to our planet. *The Astronomy and Astrophysics Review* 21–65 (2013).
- Sidle, R. C. In Comet/Asteroid Impacts and Human Society. *An Interdisciplinary Approach* (eds. Bobrowsky, P. T. & Rickman, H.) 383–398 (Springer, Berlin-Heidelberg, 2007).
- Fulchignoni, M. & Barucci, M. A. The Near Earth Objects: possible impactors of the Earth. *Comptes Rendus Physique* **6**(3), 283–289 (2005).
- Chesley, S. R., Chodas, P. W., Milani, A., Valsecchi, G. B. & Yeomans, D. K. Quantifying the Risk Posed by Potential Earth Impacts, *Icarus* **159**(2), 423–432 (2002).
- Micheli, M., Koschny, D., Drolshagen, G., Hainaut, O. & Bernardi, F. An ESA NEOCC Effort to Eliminate High Palermo Scale Virtual Impactors, *Earth Moon Planets* **113**, 1–13 (2014).
- Bobrowsky P. T. & Rickman H. Comet/Asteroid Impacts and Human Society. *An Interdisciplinary Approach* (Springer, Heidelberg, 2007).
- Milani, A., Chesley, S. R., Sansaturio, M. E., Tommei, G. & Valsecchi, G. B. Nonlinear impact monitoring: line of variation searches for impactors. *Icarus* **173**, 362–384 (2005).
- Keeney, R. & Raiffa, H. *Decisions with multiple objectives: preferences and value tradeoffs* (Wiley, New York, 1976).
- Roy, B. Classement et choix en présence de points de vue multiples (la méthode ELECTRE). *La Revue d'Informatique et de Recherche Opérationnelle (RIRO)* **8**, 57–75 (1968).
- Saaty, T. L. *The Analytic Hierarchy Process* (McGraw Hill International, 1980).
- Hwang, C. L. & Yoon, K. *Multiple Attribute Decision Methods and Applications* (Springer, Berlin Heidelberg, 1981).
- Brans, J. P., Mareschal, B. & Vincke, Ph. *PROMETHEE: A new family of outranking methods in multicriteria analysis*. In J. P. Brans, editor, North-Holland, Amsterdam, operational Research, 477–490 (1984).
- Yager, R. R. On ordered weighted averaged aggregation operator in multicriteria decision making. *IEEE Transaction on Systems and Cybernetic* **18**, 183–190 (1998).
- Saaty, T. L. *Decision Making With Dependence and Feedback: The Analytic Network Process* (Pittsburgh, PA, USA: RWS Publ., 1996).
- Opricovic, S. *Multi-Criteria Optimization of Civil Engineering Systems* (Faculty of Civil Engineering, Belgrade, 1998).

22. Mardania, A. Jusohb, A., Nora, K. M. D., Khalifah, Z., Zakwana, N. & Valipourb, A. Multiple criteria decision-making techniques and their applications – a review of the literature from 2000 to 2014. *Economic Research-Ekonomika Istraživanja* **28**(1), 516–571 (2015).
23. Chodas, P. & Baalke, R. Sentry Risk Table at the NASA Near Earth Object Program (Impact Risk). National Aeronautics and Space Administration. <http://neo.jpl.nasa.gov/risk/> [accessed 03.17.16].
24. Milani, A., Chesley, S. R., Sansaturio, M. E., Bernardi, F., Valsecchi, G. B. & Arratia, O. Long term impact risk for (101955) 1999 RQ36. *Icarus* **203**, 460–471 (2009).
25. Campins, H., Morbidelli, A., Tsiganis, K., de Leon, J. & Licandro, J. The origin of asteroid 101955 (1999 RQ36). *The Astrophysical Journal Letters* **721**, 53–57 (2010).
26. Lauretta, D. S., Drake, M. J., Binzel, R. P., Campins, H., Chesley, S. R., Clark, B. E., Delbo, M., Emery, J. P., Hergenrother, C. A., Nolan, M. C. & Scheeres, D. J., and the rest of the OSIRIS-REx Team. Asteroid (101955) 1999 RQ36: Optimum target for an asteroid sample return mission. 73rd Annual Meteoritical Society Meeting (2010).
27. Farnocchia, D. & Chesley, S. R. Assessment of the 2880 impact threat from Asteroid (29075) 1950 DA. *Icarus* **229**, 321–327 (2014).
28. Saaty, T. L. *Group decision making and the AHP* (Springer, New York; 1989).
29. Saaty, T. L. *Fundamentals of decision making and priority theory with the AHP* (Pittsburgh, PA, USA: RWS Publ., 1994).
30. Forman, E. H. Random indices for incomplete pairwise comparison matrices. *European Journal of Operational Research*. **48**, 153–155 (1990).
31. Alonso, J. A. & Lamata, M. T. Consistency in the analytic hierarchy process: a new approach. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems* **14**(4), 445–459 (2006).
32. Shahabi, H. & Hashim, M. Landslide susceptibility mapping using GIS-based statistical models and Remote sensing data in tropical environment. *Scientific reports* **5**, 9899 (2015).
33. Triantaphyllou, E. *Multi-criteria decision making methods: a comparative study* (Kluwer Academic Publishers, Dordrecht, 2000).
34. Sánchez-Lozano, J. M., García-Cascales, M. S. & Lamata, M. T. Comparative TOPSIS-ELECTRE TRI methods for optimal sites for photovoltaic solar farms. Case study in Spain. *Journal of Cleaner Production* **127**, 387–398 (2016).
35. Wang, T. C. & Chang, T. H. Application of TOPSIS in evaluating initial training aircraft under a fuzzy environment. *Expert Systems with Applications* **33**, 870–880 (2007).
36. K. Yoon. Systems Selection by Multiple Attribute Decision Making. *Ph.D. Dissertation* (Kansas State University, Manhattan, Kansas, 1980).

Acknowledgements

The authors express their gratitude to anonymous reviewers whose suggestions, comments, and remarks have allowed us to enhance the quality of this paper. They would like also to thank the group of four NEO experts from National Aeronautics and Space Administration (NASA) that allowed them to obtain the criteria weights in this work the on the basis of their expertise in the area. On the other hand, J.S.L. is partially supported by grants TIN2014-55024-P from Spanish Ministry of Economy, P11-TIC-8001 from Junta de Andalucía (including FEDER funds), and Grant 19882-GERM-15 from Fundación Séneca (Murcia). M.F.M. acknowledges the partial support of grant No. 19219/PI/14 from Fundación Séneca of Región de Murcia and grant No. MTM2014-51891-P from Spanish Ministry of Economy.

Author Contributions

M.F.M. designed the empirical experimentation in this work, collected data, partially wrote the manuscript, revised it, and contributed some conclusions regarding the present study. J.S.L. performed some MCDM procedures in this work, including AHP and TOPSIS approach, and analyzed data. He was also involved in the study design. J.S.L. and M.F.M. contributed equally to the study. Both authors discussed the results and commented on the manuscript.

Additional Information

Supplementary information accompanies this paper at <http://www.nature.com/srep>

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Sánchez-Lozano, J. M. and Fernández-Martínez, M. Near-Earth object hazardous impact: A Multi-Criteria Decision Making approach. *Sci. Rep.* **6**, 37055; doi: 10.1038/srep37055 (2016).

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This work is licensed under a Creative Commons Attribution 4.0 International License. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder to reproduce the material. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>

© The Author(s) 2016