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Evaluation of NEA deflection techniques. A Fuzzy Multi-Criteria Decision Making analysis for Planetary Defense

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Highlights

- Four deflection techniques for asteroids are assessed.
- A combination of MCDM methods with fuzzy logic is carried out
- Linguistic labels and fuzzy numbers characterize the qualitative criteria.

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Abstract

Current statistics on the flux of impactors on the Earth reveal that asteroids with a diameter larger than few hundreds of meters are unlikely to reach the Earth's orbit, although their potential effects on the life of our planet could be quite catastrophic. The present article assesses a set consisting of four deflection approaches, namely: kinetic impactor, ion beam deflection, enhanced gravity tractor, and laser ablation to be applied to mitigate a hypothetical impact with an asteroid smaller than 250 meters in diameter. This size range corresponds to the most common impactors that occur in timescales of less than 100.000 years. With the current discovery rate for small asteroids, such a range of diameters could be of interest to assess a future impact forecast, and quantify our capacity to react in time. To achieve this, a set of eight criteria are used: build time; active deflection duration; asteroid rotation; asteroid composition; asteroid structure; asteroid shape; level of maturity of a NEA deflection technique; and mission risk. This assessment is carried out with a combination of Multi-Criteria Decision Making tools and fuzzy logic, which enables proper management of imprecise criteria. The valuable knowledge provided by a group of experts enabled the importance of each attribute and the evaluation of these NEA deflection techniques to be quantified. Our results suggest that the kinetic impactor is the best option to deflect mid-size NEAs, whereas for larger asteroids, enhanced gravity tractor, and laser ablation become to be more appropriate.

Keywords: Near Earth Asteroid (NEA), deflection techniques for asteroids, Multi-Criteria Decision Making (MCDM), Fuzzy Logic, Analytic Hierarchy Process (AHP), TOPSIS (Technique for Order of Preference by Similarity to ideal Solution)

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1. Introduction

Meteoroids arrive at the Earth every day, principally as fragile aggregates and small rocks that are consequence of the decay of comets and asteroids, and the amount of mass delivered reach a mean of approximately 100 tons [1]. Even though larger objects are unlikely to reach the Earth's orbit, the effects that a potential impactor might induce in both the climate and life on our planet could be quite catastrophic. Some events of that nature already occurred in the past and are well-known. Among them, we could highlight the Cretaceous-Paleocene extinction (which took place 64 million years ago), caused by a 10 km wide impactor [2] [3]. In 1908, a low altitude breakup (5 – 10 km) of an asteroid with an estimated diameter ranging from 30 to 50 meters gave rise to what is known as the Tunguska event (1908) [4], which destroyed around 2000 km² of sparsely populated forest. More recently, in February 2013, more than 1500 people were injured by the breakup of a bolide at a high altitude (30 km) with an estimated diameter of 20 m and an estimated weighted of 12000 tons that entered the atmosphere of the Earth at a relative velocity of 19 km/s [2] [5] [6].

The term Near Earth Object (NEO) refers to either comets or asteroids with a perihelion distance less than 1.3 astronomical units (around 195 million km). According to [7], Near-Earth Comets (NECs) consist of short-period comets with orbital periods under 200 years (and perihelion distances less than 1.3 au). Since the orbits of near-Earth comets are mostly spent far away from Earth, several efforts have been made in the study of what are called near-Earth asteroids (NEAs) [2]. Notwithstanding, most of the NEO objects are asteroids, named Near-Earth Asteroids (NEAs). Such asteroids, in turn, are allocated to four groups, namely, Atiras, Atens, Apollos, and Amors, according to the following orbital elements: semi-major axis (a), aphelion distance (Q), and perihelion distance (q), for which the same notation as in [7] is used next. Specifically,

- those asteroids with $a < 1.0$ au and $Q < 0.983$ au are assigned to the Atira class, with their orbits being fully contained within the Earth's. Such a denomination derives from the object 163693 Atira.
- The Atens category (named after asteroid 2062 Aten) consists of all those NEAs with $a < 1.0$ au and $Q > 0.983$ au. It is worth noting that their orbits cross the Earth's with semi-major axes being smaller than the one of the Earth.
- Apollo objects are characterised by $a > 1.0$ au and $q < 1.017$. Such asteroids cross the Earth's orbit with their semi-major axes being larger than the Earth's. Such a denomination arises from asteroid 1862 Apollo.
- Finally, the Amor class contains all those NEAs with $a > 1.0$ au and $1.017 < q < 1.3$ au. Their orbits are exterior to the Earth's but interior to the Mars'. That category was (named after asteroid 1221 Amor).

Among the NEA population, we should highlight potentially hazardous asteroids (PHA), i.e., NEAs with a minimum orbit interception distance (MOID) of less than 0.05 astronomical units with the Earth's orbit and by an absolute magnitude not greater than 22.0 with

an expected albedo equal to 14% (i.e., an estimated diameter greater than 140 m). Such asteroids are able to make threatening close approaches to the Earth. Accordingly, these must be thoroughly tracked since small perturbations in their orbits may put them onto a collision course with the Earth [8] [9]. On the other hand, the Arjuna class (named in honour of a warrior from the Hindu mythology) is assigned those NEOs which present (almost circular) orbits that are quite similar to the Earth's, thus having low eccentricity and inclination, and orbital periods close to one year. The orbits of Arjunas are quite accessible in the sense that only low delta-v are required for return or outbound trajectories. It is clear that the definition of Arjuna asteroids presents some overlapping with the aforementioned Aten, Amor, and Apollo categories [10].

According to [2], three main reasons foster the interest in NEAs, namely, scientific knowledge (e.g., regarding the origins of the Solar System), planetary defense, and mining. Following the above, the present paper will focus on the study of NEAs from the viewpoint of planetary defense.

Some effort has been made to develop the idea of redirecting a NEA out of a risky trajectory with the Earth, at least as a preliminary proof of concept. For instance, NASA introduced the Asteroid Redirect Mission (ARM) in 2013, which considered the redirection of small (i.e., less than 8 meters in diameter) asteroids and the extraction of a small (less than 4 meters) boulder from the surface of a wide asteroid and placing it on a distant retrograde orbit around the Moon [11]. The later option could be considered as a preliminary test of our technical capacity to catch and deliver an asteroid to a safe environment although certainly such an option was not a redirection of a small PHA properly said.

Unfortunately, despite its scientific and technological interest, that project proposal was cancelled in late 2017 [12]. Nevertheless, several promising approaches to redirect NEAs have already been posed, even though the technology behind them has yet to be fully developed. In this way, it is worth pointing out that the Double Asteroid Redirection Test (DART) will be the first in situ demonstration of a KI technique to deflect the motion of an asteroid in space, formerly applied to the satellite of binary NEA (65803) Didymos [13].

Properly speaking, we should distinguish between deflection methods and redirection techniques. Thus, the aim of deflection techniques only consists in modifying the trajectory of a NEA to avoid a potential impact with the Earth, whereas the goal of redirection is to impinge a controlled change in the orbit of the asteroid with a further purpose. Among deflection techniques, we should mention kinetic impactor and nuclear blast. On the other hand, (enhanced) gravity tractor, ion beam, tugboat, mass driver, and laser ablation/sublimation belong to the class of redirection methods (see [2] and references therein). In this paper, however, we shall understand a deflection approach as being either a redirection method or a deflection technique.

The main goal in the present article is to evaluate a set consisting of four selected deflection approaches, namely: kinetic impactor; ion beam deflection; enhanced gravity tractor; and laser ablation by a set of criteria, i.e., build time; active deflection duration; asteroid rotation; asteroid composition; asteroid structure; asteroid shape; **level of maturity of a NEA deflection technique**; and mission risk. To achieve this, certain tools from Multi-Criteria Decision Making (MCDM) theory are applied. An MCDM problem seeks the best option

from a set of alternatives with respect to a set of attributes, and to deal with them, all that information is arranged in the decision matrix [14]. A family of MCDM procedures is available in the literature from the 1980s, including widely used algorithms such as ELECTRE, OWA, PROMETHEE, VIKOR, and ANP, to quote some of them. Interestingly, MCDM techniques have already been applied to study NEAs. For instance, in [15] a population of 101 PHAs with estimated diameters greater than 50 m was ranked by a set of seven criteria. The calculations were developed from the information available in the Risk and Impact tables from NASA's Near-Earth Object Program, by applying a combination of AHP and TOPSIS approaches. The ranking obtained for those objects was found to be consistent with the Palermo scale to measure the level of hazard of a potential impactor. On the other hand, a novel MCDM approach called RIM was applied in [14] in order to assess sets of potential impact dates of PHAs by choosing the three objects 2009 FD, 1950 DA, and 1999 RQ36 (Bennu), as ideal alternatives.

The present paper assesses the four deflection approaches named above under the influence of a set of criteria whose nature is qualitative instead of quantitative. To do this, we shall use a combination of MCDM techniques and fuzzy logic, consisting of a fuzzy version of the AHP together with a fuzzy version of the TOPSIS approach. This enables imprecise criteria to be properly managed [16]. **As such, the application of that combination of MCDM techniques and fuzzy logic to the astronautical field constitutes the novelty in the present work.** It should also be mentioned that the valuable knowledge as provided by a group of experts, whose collaboration was required by the authors, enabled the relative importance of the weights of the criteria as well as the evaluation of the selected NEA deflection approaches by linguistic labels to be quantified.

The structure of this article is as follows. Section 2 contains the foundations on fuzzy logic and the two MCDM techniques applied in this study, namely, (fuzzy) AHP and (fuzzy) TOPSIS. In Section 3 we deal with the assessment of the four NEA deflection approaches. Specifically, we describe the sets of alternatives and criteria, and calculate the weights of the criteria by homogeneous aggregation of the judgments of the experts. Moreover, the alternatives are evaluated through distinct sets of linguistic labels by each expert of our advisory board. Our results as well as a discussion regarding them appear in Section 4. Some additional remarks concerning the so-called ΔV parameter are provided in Section 4.1. A double sensitivity analysis is carried out in Section 5. Thus, while the first analysis consists of a variation of the weights of the criteria to verify if our results are consistent, the latter one regards the **importance of the assumption consisting of the asteroid size**. Finally, Section 6 contains our main conclusions.

2. Methodology

2.1. Fuzzy logic and fuzzy sets

Human thinking sometimes turns to prior experience when a decision has to be made; new situations may appear to be similar to, but not exactly equal to, a previous background. Fuzzy logic offers an alternative to classical logic; introducing a certain level of ambiguity when objects or situations must be evaluated.

Fuzzy sets and membership functions were introduced from a mathematical viewpoint in 1965 with the aim of modeling the level of vagueness and uncertainty in human thinking [17]. It should be noted that the domain of a membership function is the closed unit interval, $[0, 1]$, rather than the set $\{0, 1\}$. Therefore, the relative membership of an object to a given set could be gradually measured, in contrast to classical logic, where that membership is determined by an absolute approach.

The use of fuzzy logic becomes appropriate in several real-life situations, since determining the rules of membership of objects to categories is not always a trivial task. For instance, we may think that 25-year-old people could be assigned to the category of “young people”. However, somebody may also assign 35-year-old people to that same category. Going beyond that, the category itself could be conditioned by a context.

In a fuzzy context, the level of membership of an object to a certain category is measured through a real number lying in the closed unit interval $[0, 1]$. More precisely, the more likely it is that an object belongs to a category, the closer to 1 its level of membership is. Similarly, the more unlikely it is that it belongs to such a category, the closer to 0 its degree of membership becomes.

Mathematically, let U be a universe of discourse and A be a subset of U . A membership function, $\mu_A : U \rightarrow [0, 1]$, is defined as an association rule that maps each element $x \in U$ to the degree of membership of x to A , $\mu_A(x) \in [0, 1]$. On the other hand, if the nature of the involved criteria is qualitative, then the previous concept of a membership function can be further extended allowing the use of linguistic labels and variables, which become more accurate than crisp numbers in a qualitative context [18].

Every function $\mu_A : U \rightarrow [0, 1]$ may describe a membership function associated with a fuzzy set at first glance. Such a function depends on the concept it represents as well as the context it is applied to. Some membership functions are widely applied in practice, such as the LAMBDA (also triangular) function, the PI (also trapezoidal) function, and also the Gaussian function.

By a triangular fuzzy number, we shall understand an element $x \in U$ whose image by a membership function, $\mu_A : U \rightarrow [0, 1]$, admits the following expression:

$$\mu_A(x) = \begin{cases} \frac{x-a}{b-a} & \text{if } a \leq x \leq b \\ \frac{x-c}{b-c} & \text{if } b \leq x \leq c \\ 0 & \text{otherwise,} \end{cases} \quad (1)$$

where a, b , and c are real numbers. Notice that b coincides with the mode of the values in the support interval $[a, c]$ and satisfies that $f(b) = 1$. For illustration purposes, upcoming Fig. 1 depicts the membership function of a triangular fuzzy number.

[Figure 1 about here.]

In this paper, we will use triangular fuzzy numbers and consider the LAMBDA (triangular) membership function due to their simplicity and easy handling.

To conclude this section, we would like to point out that arithmetic calculations involving triangular fuzzy numbers, as well as sorting procedures to turn fuzzy numbers into real values, can be found in [19] [20] [21].

2.2. The Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process methodology (AHP in the sequel) is a well-established, flexible, and robust MCDM approach to address complex decision problems [22].

It is noteworthy that AHP deals with the following tasks:

- (i) “modeling” a complex decision problem by a hierarchy of alternatives and criteria to achieve a goal;
- (ii) making comparisons between pairs of elements from each level of the hierarchy with respect to all the criteria in the previous level; and
- (iii) vertically synthesizing the judgments along all the levels of such a hierarchy.

We would like to point out that in this paper, AHP will only be applied to obtain the weights of the criteria. However, it does also enable the impact of each alternative on the overall objective of the hierarchy to be quantified.

Next, we shall mathematically describe the running of the AHP procedure. Firstly, let us assume that all the judgments provided by the decision makers involved in the study are arranged by pairs of criteria, (C_i, C_j) , and displayed in the following $n \times n$ matrix:

$$C = \begin{pmatrix} C_1 & C_2 & \dots & C_n \\ c_{11} & c_{12} & \dots & c_{1n} \\ c_{21} & c_{22} & \dots & c_{2n} \\ \vdots & \vdots & \dots & \vdots \\ c_{n1} & c_{n2} & \dots & c_{nn} \end{pmatrix} \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} \quad (2)$$

Note that the entry c_{ij} of that matrix provides some valuable information regarding the relative importance of the criterion C_i with respect to the criterion C_j , i.e., $c_{ij} \approx (w_i/w_j)$. Additionally, the matrix C satisfies the four properties stated below:

1. $c_{ij} \approx (w_i/w_j)$ for each $i, j = 1, 2, \dots, n$.
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 C_i is more important than C_j , then we have that $c_{ij} = (w_i/w_j) > 1$.

In other words, C is a reciprocal and positive matrix with 1's in its diagonal. As such, the decision makers only have to provide judgments for those comparisons involved in a triangular (either the upper or the lower) submatrix of C . It is worth mentioning that the so-called Saaty's scale provides the values that are usually assigned to the c_{ij} 's, which are integers between 1 and 9 and their (rational) reciprocals, as well. All the linguistic preferences for decision makers throughout the comparison process by pairs are displayed in Table 1.

[Table 1 about here.]

Note that the number of necessary judgments, L , to be made by the decision makers to fill the upper triangular submatrix of C is given by the following expression:

$$L = \frac{n}{2}(n-1), \quad (3)$$

where n is the number of rows (resp., columns) of C .

Moreover, the weights of the criteria are given by the eigenvector associated with the maximum of the eigenvalues, " $\lambda_{\max}$ ", of C . Interestingly, it holds that the eigenvector-based method to calculate the weights of the criteria throughout the AHP process allows the consistency of the preferences of each decision maker to be measured. To do this, the consistency index (CI) can be calculated by means of the following expression: $CI = (\lambda_{\max} - n)/(n - 1)$. Thus, $\lambda_{\max}$ is greater than n provided that the preferences of the decision maker exhibit some minor inconsistency. The consistency ratio, CR, was defined by Saaty as $CR = CI/RI$, where RI (the Random Index) is calculated by the mean of the CI's (see Table 2) for random matrices by applying Saaty's scale (Forman, 1990). In this way, a matrix is said to be consistent (in the Saaty sense) provided that $CR < 0.1$.

[Table 2 about here.]

On the other hand, if the nature of the decision problem is fuzzy rather than crisp, the weights of the criteria are calculated by means of the normalized geometric mean, given by the expression:

$$w_i = \frac{\left(\prod_{j=1}^n (a_{ij}, b_{ij}, c_{ij})\right)^{\frac{1}{n}}}{\sum_{i=1}^m \left(\prod_{j=1}^n (a_{ij}, b_{ij}, c_{ij})\right)^{\frac{1}{n}}} \quad (4)$$

with (a_{ij}, b_{ij}, c_{ij}) being a fuzzy number.

2.3. The fuzzy TOPSIS (FTOPSIS) method

The Technique for Order Performance by Similarity to Ideal Solution (TOPSIS, hereafter) has become a widely applied methodology from MCDM theory. It was first contributed in [24]. The underlying idea in such a procedure consists in choosing the best alternative, which is the one that keeps the greatest distance from the Negative Ideal Solution (both (B) and (D) in Fig. 2) as well as the lowest distance from the Positive Ideal Solution, labeled as (C) in Fig. 2.

[Figure 2 about here.]

As such, the best choice becomes a compromise solution following the decision makers' preferences. Several reasons support the application of TOPSIS in MCDM (see, e.g., [25]):

- (i) The logic running under TOPSIS is light and comprehensible.

- (ii) The necessary calculations are easy.
- (iii) When looking for the best option, TOPSIS easily treats each attribute from a mathematical viewpoint.
- (iv) The comparison process in TOPSIS also involves the relative importance of each criterion.

A fuzzy version of the classical TOPSIS approach (FTOPSIS) was applied to rank the four NEA deflection techniques considered throughout this study (see Section 3.1). The calculations involving linguistic labels were arranged accordingly in our implementation of that fuzzy methodology [26].

The running of FTOPSIS involves the following steps.

Step 1 Generating a performance decision matrix.

Let us construct an $m \times n$ matrix whose entries contain the evaluation of the i th alternative ($i = 1, \dots, m$) with respect to the j th attribute ($j = 1, \dots, n$) (see Table 3). Such evaluations are quantified through the performance score of each option by each attribute.

[Table 3 about here.]

In Table 3, the list $W = [w_1, w_2, \dots, w_n]$ represents the weights of the criteria.

Step 2 Normalizing the decision matrix.

The next step is to normalize the decision matrix. Thus, the scale remains equal for each criterion. Let $i (= 1, \dots, m)$ be a fixed column and let x_{ij} be any entry in that column. Then divide x_{ij} by the norm of the list containing all the elements in that column, i.e.,

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^n x_{ij}^2}} : j = 1, \dots, n, i = 1, \dots, m. \quad (5)$$

Step 3 Calculating the weighted normalized decision matrix.

Recall that fuzzy AHP provided the weights of the criteria. In particular, the sum of all the weights equals the unit. It is worth mentioning that the entries of the weighted normalized decision matrix are calculated through the following expression:

$$v_{ij} = w_j \otimes n_{ij} : j = 1, \dots, n, i = 1, \dots, m. \quad (6)$$

where the weights w_j 's satisfy that $\sum_{j=1}^n w_j = 1$. In this paper, said weights are calculated through the fuzzy AHP methodology.

Step 4 Finding both the positive ideal solution and the negative ideal solution.

Let J denote the set of criteria associated with profits and let J' be the set containing all the criteria which correspond to losses. Two sets have to be calculated in this step. In fact, while $A+$ provides the greatest performance scores (with respect to the

positive ideal solution), A^- displays the worst performance scores (with regard to the negative ideal solution) (see Eq. (7)).

$$\begin{aligned} A^+ &= \{v_1^+, \dots, v_n^+\} = \left\{ \max_{i=1, \dots, m} \{v_{ij} : j \in J\} \min_{i=1, \dots, m} \{v_{ij} : j \in J'\} \right\} \\ A^- &= \{v_1^-, \dots, v_n^-\} = \left\{ \min_{i=1, \dots, m} \{v_{ij} : j \in J\} \max_{i=1, \dots, m} \{v_{ij} : j \in J'\} \right\}. \end{aligned} \quad (7)$$

Step 5 Determining the separation distances.

A pair of distances of separation must be calculated for each alternative involved in the study. Thus, one of them is determined with respect to the positive ideal solution, whereas the other one must be calculated with respect to the negative ideal solution. To do so, the Euclidean distance is used as follows. For each $i = 1, \dots, m$, let us calculate

$$d_i^+ = \left(\sum_{j=1}^n (v_{ij} - v_j^+)^2 \right)^{\frac{1}{2}}, \quad d_i^- = \left(\sum_{j=1}^n (v_{ij} - v_j^-)^2 \right)^{\frac{1}{2}} \quad (8)$$

Step 6 Calculating the relative closeness to the ideal solution.

A measure of the (relative) closeness of each alternative in the study to the positive ideal solution is obtained according to the following expression:

$$R_i = \frac{d_i^-}{d_i^+ + d_i^-} : i = 1, \dots, m. \quad (9)$$

Such a score allows all the alternatives to be ranked. Observe that a given alternative A_i becomes closer to the positive ideal solution as R_i nears 1, whereas it approaches the negative ideal solution whenever R_i lies close to 0.

Step 7 The defuzzification process.

In [27], a defuzzification process was provided, thus allowing the conversion of fuzzy numbers into real ones. With this aim, the following expression was proposed:

$$I_{\frac{1}{3}, \frac{1}{2}}(R_i) = \frac{1}{3} \left(\frac{a_i + 4b_i + c_i}{2} \right) : i = 1, \dots, m, \quad (10)$$

where such coefficients belong to the closed unit interval. In particular, the priority of the i th alternative becomes greater as its associated coefficient (according to Eq. (10)) becomes closer to the unit.

Step 8 Ranking the orders of preference. The coefficients provided by Eq. (10) for each alternative enable them to be ranked (in descending order).

3. Evaluating the NEA deflection approaches

First of all, we recall that the main goal in our study is to perform a fuzzy MCDM analysis to assess four NEA deflection approaches, i.e., enhanced gravity tractor, ion-beam

deflection, kinetic impactor, and laser ablation, with respect to a set consisting of 8 criteria (c.f. Section 3.2). With this aim, a group of experts was inquired to determine the relative importance of each criterion due to their valuable knowledge, thus allowing us to evaluate such NEA deflection techniques.

By deflecting an asteroid, we shall understand the object being accelerated just enough so it crosses the Earth's orbit by a minimum distance from the point the NEA would have crossed it in the case it had not been deflected.

The assumptions of our study are as follows. The main goal is to perform a (non-nuclear) primary deflection of (at least) 2 Earth radii (with the exception of the Kinetic Impactor) on a threatening asteroid with an estimated diameter not greater than 250 meters. The warning time, i.e., the time going from the detection of the threat to the expected date of collision varies from 5 to 30 years. All such information was provided to the experts we surveyed.

On the other hand, the allocation of a threatening NEA to an orbital group (c.f. Section 1) has not played a specific role in our study. Instead of this, some simplifying assumptions regarding orbital dynamics have been made according to Eq. (7) in [28] and Table 1 in [29]. Specifically, an approach to estimate the change of position of the asteroid, dX , in the along-track direction may be obtained by the following expression:

$$dX \simeq 3 \cdot dV \cdot T, \quad (11)$$

where dV denotes an increment of velocity, and $T = \frac{T_1}{2} + T_2$ with T_1 being the deflection duration and T_2 the coast duration after active deflection (when applicable).

3.1. The NEA deflection alternatives selected for assessment

In this section we describe the four (non-nuclear) NEA deflection techniques that were chosen in our study with the goal to achieve successfully the deflection of a threatening asteroid.

Alternative A_1 . The kinetic impactor approach (KI, hereafter) consists in placing a spaceship on a proper trajectory so as to crash into an asteroid at a high relative velocity, thus modifying both the velocity and the momentum of that NEA [29]. NASA's Deep Impact mission confirmed that it is already technically possible to collide an object at a relative high velocity: they collided a small impactor with the core of comet Tempel I on July 4, 2005 [30]. Several government agencies also prefer the deflection technology of KI due to the immediacy of its effect and also the high level of momentum it may deliver to the targeted NEA. Despite that, a great deal level of uncertainty remains with regard to the amount of effectively delivered momentum, which is related to the beta factor [31]. Despite some studies have assumed quite significant momentum multipliers (c.f., e.g., [32]), a momentum multiplier equal to 1 has been considered in this study, which means that no material is ejected away from the asteroid after the collision. This is obviously a simplistic approach that considers a lower limit for the momentum transfer with no momentum multiplication due to the materials usually

released in impact plumes (c.f., e.g., [33]). Further, while it lies out of the scope of the present study, it is noteworthy that there exists a variant of the KI whose impactor is endowed with a nuclear warhead.

Alternative A_2 . Ion beam deflection (IBD) consists of an ion thruster aboard a spacecraft (known as the “shepherd”) which points a highly collimated high-velocity ion beam at the asteroid. At the same time, a secondary thruster points in the opposite direction to keep a uniform distance from the NEA [29] [34]. In this way, a hovering distance of approximately twice the diameter of the targeted NEA renders the gravitational force of the asteroid negligible [35]. An advantage of IBD over KI is that the *rendezvous* spacecraft could be sent to the NEA in advance, thus reducing the uncertainty regarding the orbit of the object. Another advantage of IBD consists in its accurate retargeting of the impact point, a fact that becomes especially useful when dealing with large objects which may be deflected only a few Earth radii (unless a nuclear blast is employed). However, the hovering of the shepherd spaceship has not reached a sufficient level of autonomy yet. Furthermore, even greater accuracy regarding the pointing of the beam is still required [31]. Next, we state some specific assumptions considered along this paper in regard to the IBD.

- A negligible angle of impact of the ions on the surface of the NEA is supposed.
- The distance from the spacecraft to the asteroid is calculated such that the whole ion beam impinges on the asteroid.
- Also, the spacecraft is located far enough from the NEA so that its flight system is not affected by material that could be potentially ejected from the asteroid.
- The spacecraft is equipped with two thrusters. Thus, the first one fires at the asteroid whereas the second one counters the force the first thrust applies.

Alternative A_3 . Enhanced gravity tractor (EGT). Let us assume that a spacecraft is hovering over a NEA. The idea under gravity tractor (GT) technology mainly focuses on redirecting the trajectory of the targeted asteroid by employing the gravitational attraction between the spaceship and the NEA [35]. Let us further assume that the hovering spaceship extracts some regolith or rocks from the asteroid, thus increasing its own mass. That amount of mass is calculated so its thrusters at full power (and in the general direction of the asteroid) do not make the distance between the spaceship and the NEA increase. That extended approach is EGT. The gravitational force from the tractor on the asteroid body causes the redirection. With that purpose, the EGT must use its thrusters to maintain its position relative to the asteroid so as to create and maintain the desired gravitational force. It should be noted that GT (without enhancement) could play the role of a trim/observer approach though it will not be used for primary deflection purposes [29]. Additional details regarding EGT can be found in [36]. In this article, we have assumed an EGT with an unconstrained system of mass acquisition. In fact, we have considered NEAs with estimated diameters smaller

than few hundred meters, mostly exhibiting a rubble pile structure in which extracting mass from large boulders on its surface is technically feasible. A specific assumption regarding the EGT consists of the possibility that robotic spacecraft could extract some mass from the targeted NEA, which will be used to increase the gravitational mass of the spacecraft and hence, to gravitationally accelerate the NEA.

Alternative A_4 . The main idea regarding the Laser Ablation (LA) technique consists of a laser that vaporises material from the surface of the asteroid, thus leading to a recoil motion in the object. To deal with, an array of phase-locked laser amplifiers, located at a distance of about 1 km away from the asteroid, continuously discharges at the object. Thus, the clustered energy increases the temperature in the laser spot on the surface of the asteroid enough to vaporise material from its surface, which is driven out from it. Therefore, the velocity of the asteroid is increased/decreased by a reaction force induced by the ejected vaporization plume depending on whether the laser follows/leads the asteroid along its trajectory. (c.f. [29] and [35]). Interestingly, several formation settings were proposed in [37] to optimise the performance of LA. In particular, it was highlighted therein that a formation choice is preferred to the detriment of a single spaceship. In fact, as the diameter of the primary mirror increases, the radiator and laser mass increase to the point of the mass of a single spacecraft exceeds the total mass of two or more smaller size spacecrafts. Thus, the number of spacecrafts increases as the mirror aperture diameter increases (c.f. Section 4.1 in [37]). In this paper, though, we shall consider that only one LA spacecraft is involved.

There is a key difference between LA and EGT in regard to the management of the Solar-Electric ion-Propulsion (SEP) propellant the spacecraft requires to keep a uniform distance with respect to the asteroid along the deflection stage. In fact, while the thrusters of a LA spacecraft uniquely propel the spacecraft, the thrusters of an EGT spacecraft are required to propel the whole spacecraft-asteroid system. As such, the SEP propellant of a LA spacecraft has to last long enough up to be able to perform the active deflection before the Earth's orbit is reached. In this way, no coasting is needed once the active deflection has concluded (c.f. [29] [38] [39]).

Next, we state some specific assumptions we considered in regard to the LA approach. Our laser ablation mission concept implies one spacecraft equipped with a kilo-watt laser (powered by solar panels) that continuously hits the asteroid and produces a plume of ablated material inducing a small, but continuous force onto the asteroid and in the right direction to achieve the required deflection. We also suppose that the laser is positioned farther than 1 km away (at least) from the NEA in such a way that the material being ablated does not cover the optics of the laser. Obviously there are many other options that increase the deflection capacity. For example, creating an array of spacecrafts that hit the asteroid surface at once in one of several points to increase the reaction force.

For further technical details regarding each NEA deflection approach described above, we refer the reader to [8], [29], and [35].

3.2. Description of the criteria

In this paper, all the criteria described below will be evaluated from a qualitative viewpoint. With this aim, we shall employ three distinct sets of linguistic labels, as described in Section 3.5 and Table 8.

Attribute C_1 . Build time (T_b), which is defined as follows:

$$T_b = \text{Required warning time} - T_r - K_t, \quad (12)$$

where the (required) warning time is the timeframe from the discovery of the threat to the predicted date of collision; T_r denotes the *rendezvous* time; and K_t equals the sum of the active deflection time and the coasting time. **Note that the coasting time is equal to 0 with regard to KI approach.** It should also be mentioned that the time the deflection technologies need in order to achieve TRL 6 is not included in this attribute [29]. The build time is especially important when the warning time is short, which in turn, may be caused by a significant uncertainty regarding the probability of impact of the NEA with the Earth.

Attribute C_2 . Duration of the active deflection. This criterion refers to the time required to achieve a NEA deflection of (at least) twice the radius of the Earth (except for KI).

Attribute C_3 . **Importance of the assumption consisting of the rotation of the asteroid.** As our advisory board suggested, for asteroids with estimated diameters ranging from 150 to 240 meters, it is unlikely to have to deal with a fast rotator.

Attribute C_4 . **Importance of the assumption consisting of the asteroid composition.** Such a criterion may influence the effectiveness of some deflection techniques. **We note, as previously pointed out by [29] that the LA technique may not be efficient for all plausible asteroid types. For example, an asteroid composed primarily of nickel-iron might conduct away most of the laser's heat instead of ablating. In any case, such a type of asteroids are quite rare in the NEA population (c.f. [40] and references therein). In fact, about a 90% of the bodies are expected to be rocky in nature, so LA could be a good approach although for now it lacks of a mission as a proof of concept. In that sense, a solar power laser could provide a much lighter and adaptable concept to allow a future test on a small asteroid.**

Attribute C_5 . **Importance of the assumption consisting of the asteroid structure.** This criterion concerns the overall internal structure of the asteroid and its porosity rather than the friability and the structure of the surface material of the NEA. This aspect becomes crucial since some NEA deflection techniques such as KI are especially sensitive to the porosity and the internal structure of the asteroid, which could affect the momentum transfer. On the other hand, the effectiveness of LA and IBD are mostly conditioned by the friability of the surface material of the NEA. Furthermore, this could impact on the ability of EGT when collecting material from the asteroid surface.

Attribute C_6 . Importance of the assumption consisting of the asteroid shape. Targeted NEAs may present a wide range of irregular forms.

Attribute C_7 . Level of maturity of a deflection method. This criterion is related to the level of development of the technology under a NEA deflection approach.

Attribute C_8 . Mission risk. This takes into account a potential unsuccessful result of the NEA deflection mission or a technological failure itself. This is quantified separately from the TRL with the aim of identifying the specific risks that may appear in the implementation of each NEA deflection technique. A standard scale based on the Goddard risk matrix is used as a model to deal with the risk assessment (see [35] [41] [42] [43]).

3.3. The advisory board

A group consisting of 10 qualified researchers from renowned institutions filled in questionnaires sent by the authors, thus carrying out some valuable comparatives among alternatives and criteria. Their areas of expertise include NEAs as well as their deflection techniques. Specifically, the distribution of the members of our advisory board by affiliations was as follows: three researchers from the Langley Research Center and Jet Propulsion Laboratory of the National Aeronautics and Space Administration (NASA); two experts from the Planetary Defence Office and Galileo Mission of the European Space Agency (ESA); one scientist from the Laboratory of Applied Physics at the Johns Hopkins University; one researcher from the Institute for Aerospace Studies at the University of Toronto; one expert from the Institute of Space Sciences at the Spanish National Research Council; one scientist from the Department of Physics Applied to Aeronautical Engineering of the Polytechnic University in Madrid; and one Ph.D. researcher from the Department of Mathematics and SpaceDyS at the University of Pisa.

Once the judgments of the group of experts we inquired were received, the next step was to obtain the weights of the criteria. Then a qualitative assessment of the four NEA deflection methods involved in this study with respect to such attributes was obtained. Fig. 3 summarizes all the stages involved in the methodology followed in our analysis, which combines MCDM approaches (AHP and TOPSIS) with fuzzy logic.

[Figure 3 about here.]

3.4. Obtaining the weights of the criteria

The experts taking part in our study did not interact with each other. As such, a pseudo-Delphi methodology was applied to extract some knowledge from the members of our advisory board. Each expert was sent a 3-point questionnaire based on the AHP methodology, so the most appropriate answers as considered by each member were chosen. Such valuable information enabled the calculation of the weights of the criteria. The three questions that appeared in the questionnaire are as follows:

Question 1: Do you believe that the eight criteria must be assigned the same weight?

In the event that the answer was affirmative, then $w_i = 1/k$ for all $i = 1, \dots, k$, where k is the number of criteria ($k = 8$ in this study). On the contrary, if all the criteria were considered as not being equally important, the next issue in the questionnaire should be addressed. On this occasion, all the experts considered that some criteria should have a greater importance than others.

Question 2: List the criteria in descending order of importance.

In this step, each expert of the advisory board provided the order of importance of the criteria (see Table 4).

[Table 4 about here.]

Once the order of importance of the criteria had been stated by each expert of the group, a comparison among such criteria needed to be made. To do so, a final question was addressed.

Question 3: Select the labels listed in Table 1 depending on the relation of each row and each column. Please, use the set of labels (EI), (mMI), (MI), (MMI), (EMI), and their reciprocals, which correspond with Saaty's scale of valuation in the pairwise comparison process (see Section 2.2).

For illustration purposes, Table 5 shows the linguistic labels as employed by Expert 1 (E_1) to qualify her/his judgment when comparing each pair of criteria.

[Table 5 about here.]

It should be noted that nine additional matrices were obtained, similar to that displayed in Table 5 for the judgments provided by the rest of the experts when comparing pairs of criteria from a qualitative viewpoint by means of a set of linguistic labels.

The judgments provided by the group of experts through the Fuzzy AHP methodology were verified. In this way, special mention should be made to the fact that a CR was calculated for each of them. Next, for illustration purposes, we show how to calculate the CR in regard to the judgments provided by the expert E_1 . Firstly, it is considered the central value of each triangular fuzzy number from the matrix of judgments of that expert (c.f. Table 5). In fact, the central value is selected as the most representative value of the corresponding triangular fuzzy number. Hence, the vector of the weights of the criteria is obtained by calculating the normalized geometric mean for each criterion (c.f. Table 6).

[Table 6 about here.]

In this case, the eigenvalue $\lambda_{\max}$ was found to be equal to 8.202, which is somewhat larger than 8, the value that corresponds to a fully consistent matrix. According to the expressions provided in Section 2.2 to calculate both the CI and the CR, a CR equal to 0.02 was obtained. Since a CR less than to 0.1 is usually considered as acceptable, we conclude that the judgments provided by the expert E_1 are acceptably consistent.

Since all the CRs were found to be less than 0.1, such judgments did not have to be revised. Subsequently, assuming that the contribution of each expert was equally substantial when comparing each pair of criteria, a homogeneous aggregation of the results they provided was carried out by an arithmetic mean. The weights of the criteria obtained by homogeneous aggregation of the judgments of the experts appear in Table 7 described in terms of triangular fuzzy numbers.

[Table 7 about here.]

[Figure 4 about here.]

[Figure 5 about here.]

Fig. 4 highlights that the most important criteria are C_1 (Build time) and C_2 (Active deflection duration). Note that the sum of their weights, equal to 55.3% of the overall relevance, is greater than the sum of the weights of the rest. The group of experts were shown those results and, interestingly, confirmed that they were in line with their individual judgments, thus being well-balanced and quite reasonable. In addition, several interesting remarks were made by some of the experts from our advisory board. First, one of the experts pointed out that such a ranking of the criteria by their relative importance assigns greater weights to those criteria related to the mission design rather than the physical features of the object, which were assigned lower values (c.f. Fig. 5). However, attribute C_8 (Mission Risk) was assigned a lower weight. Regarding this, another expert conveyed that, although the risk of the mission is always a key factor to be considered, it could be largely mitigated after a number of missions. In fact, testing deflection technologies in advance of actual needs becomes crucial to reducing the mission risk, thus increasing the performance of the deflection mission.

Another expert of the advisory board noted that the (reasonable) assumption consisting of a limited warning time greatly influenced the three most important criteria, namely, C_1 (Build Time), C_2 (Active deflection duration), and C_7 (Level of maturity). Indeed, the criterion consisting of Build Time (C_1) is especially important whenever a short warning time is available, which is a very likely scenario due to the significant uncertainty with regard to the probability of an impact with the Earth, which may result in a “wait and see” attitude by political leaders. As such, C_1 , C_2 , and C_7 become the most important criteria under a scenario of a limited warning time. On the other hand, the relative importance of such criteria would decrease in the (unlikely) case that a potential impactor may be confirmed with a warning time of at least a decade.

According to one expert of the board, the first ranked attribute related to the nature of the target object, i.e., C_4 (Asteroid composition, which appeared in 4th position) should

be considered as being quite important in this study since it induces a first order effect on the mass of the asteroid. In this way, another expert indicated that the composition of the asteroid as well as its local topology strongly influence the direction and the quantity of asteroid material ejecta at the impact location. Hence, the risk (especially in the case of KI) that the impact will not properly deflect the asteroid may become extremely high [44].

Another expert highlighted that the physical size or the size uncertainty of the asteroid should also have a first order effect on deflection approach effectiveness (even for objects with estimated diameters ranging from 140 to 250 m).

Such comments encouraged us to analyze in depth **the importance of the assumption consisting of the asteroid size** in the assessment of the alternatives. This was verified by carrying out an additional sensitivity analysis (see Section 5.2).

3.5. Evaluating the alternatives

In the previous section, all the criteria involved in this article were evaluated using linguistic labels. As such, the weights of the criteria were obtained by homogeneous aggregation of the judgments of the experts through fuzzy AHP. Next, the members of our advisory board were asked to assess each of the four NEA deflection alternatives with respect to each criteria. Three distinct sets of linguistic labels, namely, L_1 , L_2 , and L_3 had to be used to achieve this. All the tags in each set of linguistic labels as well as their associated triangular fuzzy numbers are presented in Table 8.

[Table 8 about here.]

It should be noted that the group of experts applied the set of labels L_1 to assess both criteria C_1 (Build time) as well as C_2 (Active deflection duration) for each alternative. The set of labels L_2 allowed the experts to evaluate criteria C_3 (asteroid rotation), C_4 (asteroid composition), C_5 (asteroid structure), and C_6 (asteroid shape) for each of the four NEA deflection technologies involved in this study. Finally, the experts were asked to assess the last two criteria, i.e., C_7 (Actual level of maturity of a deflection technique) and C_8 (Mission risk) by linguistic labels of type L_3 . It should also be mentioned that all the criteria, with the exception of C_7 (Actual level of maturity of a deflection technique) were to be minimized.

Table 9 shows our decision matrix, which contains the assessments for all the eight criteria from the viewpoint of each expert we surveyed for each deflection technology involved in this study. The rows in that matrix show the experts' assessments of each alternative with respect to all the criteria (related to columns in that matrix).

Once the decision matrix had been obtained, the fuzzy TOPSIS approach (see Section 2.3) was properly applied to quantify the relative effect of every alternative with respect to each attribute.

[Table 9 about here.]

4. Results and discussion

Once the weights of the criteria had been determined (see Table 7), the FTOPSIS methodology was applied with the aim of providing a ranking for all the alternatives involved in this study. Fig. 6 depicts this ranking of alternatives in terms of fuzzy numbers according to their relative proximity. In addition, Table 10 displays a ranking of those alternatives in terms of crisp (real) numbers which was obtained by a defuzzification process [27].

[Figure 6 about here.]

[Table 10 about here.]

The results obtained were as follows. According to our group of experts, the NEA deflection alternative ranked in first position was found to be A_1 (Kinetic Impactor, KI). The following ranked alternatives were A_2 (Ion Beam Deflection, IBD), and A_3 (Enhanced Gravity Tractor, EGT), respectively. They were ranked quite close to each other but far away from KI. Alternative A_4 (Laser Ablation, LA) was ranked in the last position.

The group of experts were asked for an appraisal with regard to our combination of fuzzy AHP and FTOPSIS based rankings that we obtained for the NEA deflection techniques involved in this study. As a result, they confirmed the adequacy of such rankings under a limited warning timeframe and the lack of a practical demonstration of such techniques. We shall now comment on some interesting judgments and on the remarks they provided us with.

According to the group of experts, the first position for KI in our ranking is supported by the fact that said deflection technique is currently the best choice and does indeed have great promise for deflection purposes, and also because it has have been studied for a longer time than the other alternatives. Even so, some experts mentioned that KI, as an uncontrolled deflection method, may generate significant uncertainties since it is not very clear how the orbit of the NEA will change once it has been impacted. Additionally, will the impact cause fracturing that might not fully mitigate the impact hazard? One would hope that some of these questions will be partially addressed by NASA's DART mission.

The second position for the Ion Beam Deflection (IBD) in detriment of the Enhanced Gravity Tractor (EGT) was also supported by our group of experts. They argued that it becomes necessary to check the actual net force on the asteroid from the mass of the EGT. In fact, a very large mass is needed to make even small net changes to the trajectory [35]. Nevertheless, the ability of EGT for significant reductions in deflection duration as compared to a traditional GT has already been analyzed [45].

The last position for Laser Ablation (LA) did not surprise the group of experts at all. Although they highlighted that LA has indeed some significant advantages (no direct surface interaction, effective against various target compositions, and scalable with power and multiple laser systems, e.g.), they also pointed out a lack of demonstration of a powerful enough laser system.

The experts further expressed concerns regarding operating high-power laser systems in space, the uncertainty of their effect on the asteroid parameters, and on the readiness of

that technology. In spite of these disadvantages, our experts stated that it is a promising approach for a future planetary defense capability. It was in fact recommended as a long-term technique as part of the Comet/Asteroid Protection System (CAPS) [46].

4.1. A remark on the ΔV parameter

According to one of the experts taking part in our survey, the so-called ΔV parameter constitutes a key factor to take into account. It measures the impulse velocity increment imparted to an Earth-crossing asteroid (ECA) [47]. Based on the variations of ΔV , it could be possible to devise and build NEA deflection strategies to prevent possible catastrophes. An optimal ΔV and the deflection strategy depend on the size of the asteroid and its orbital elements, as well as on the amount of warning time available; the influence of that parameter had been previously analyzed [35] [46]. Those reports concluded that although the best optimal impulse change in velocity (ΔV) and a suitable NEA deflection technique should be carefully analyzed whenever an impacting object is discovered, the Laser Ablation (LA) strategy presents significant advantages, including the potential to induce controlled orbit modifications of Earth-crossing objects. **It is also worth pointing out that other NEA deflection approaches, such as EGT and IBD, are also able to induce controlled orbit modifications.**

5. Sensitivity analyses

In order to validate the robustness of the results displayed in Section 4, a double sensitivity analysis was carried out. First of all, the FTOPSIS methodology was applied again to rank the four NEA deflection techniques involved in this article (KI, IBD, EGT, and LA) under the assumption that each of the criteria have been assigned the same weight.

On the other hand, one of the experts we surveyed highlighted that the physical size should also have a first order effect on the effectiveness of such deflection techniques, even for NEAs with estimated diameters ranging from 140 to 250 meters, as is the case. As such, we decided to analyze the influence of that parameter in our rankings by carrying out an additional sensitivity analysis.

5.1. Varying the weights of the criteria

Both Fig. 7 (for triangular numbers) and Table 11 (for crisp numbers) display the new rankings we obtained by applying FTOPSIS under the assumption that all the criteria are equally weighted.

[Figure 7 about here.]

[Table 11 about here.]

Even though the positions of the alternatives are the same in both rankings, it holds that the differences among the three first ranked alternatives have been significantly reduced, particularly with regard to the first ranked alternatives (KI and IBD). As such, a cluster

among them appears in the event that all the criteria are assumed to be equally important. It is also noteworthy that LA remains in the last position, with its difference with respect to the previous ranked NEA deflection techniques being increased.

On the one hand, it bears up that the weights of the criteria as calculated by the judgments provided by the group of experts via AHP do not influence the ranking of the NEA deflection alternatives. However, their participation in that stage of our study was quite valuable, thus allowing insight to fully appreciate the differences among all the alternatives.

5.2. *On the importance of the asteroid size*

As commented above, one of the experts we surveyed suggested to us that the **importance of the assumption consisting of the asteroid size** should be evaluated, since the mass of an asteroid approximately varies as the cube of its diameter. The combination of the NEA size uncertainty and the uncertainty regarding its density enlarges the range of the estimated mass of the object, even in the range of diameters this study considered.

Thus, being encouraged by that interesting proposal, we analyzed the influence of of such a new criterion with regard to our assessment of the four NEA deflection techniques involved in this study. To do so, a new survey was conducted to evaluate the four alternatives based on the set of fuzzy labels L_3 (see Table 8). That survey, that was filled out by this expert, allowed us to determine the **importance of the assumption consisting of the asteroid size** for each of the four NEA deflection techniques. Table 12 in our manuscript summarizes the results that were obtained. This way, a new column containing the linguistic labels expressed by triangular fuzzy numbers was added to our decision matrix.

[Table 12 about here.]

Next, we proportionally varied the weights of the remaining criteria to determine the relative influence of that new attribute. The criterion **importance of the assumption consisting of the asteroid size** was assigned different ratios, i.e., 10%, 20%, 25%, and 50% of the overall relevance. Proportionally to their weights (c.f. Table 7), the remaining criteria ($C_1 - C_8$) were assigned the ratios 90%, 80%, 75%, and 50% of the overall relevance. Once all the stages of the FTOPSIS methodology were carried out, a new ranking was obtained. The results appear in both Table 13 and Fig. 8.

[Table 13 about here.]

[Figure 8 about here.]

In light of the obtained results, it is upheld that, as the relevance of the **assumption consisting of the asteroid size** increases, the Enhanced Gravity Tractor (EGT) and Laser Ablation (LA) techniques become the best alternatives according to FTOPSIS. On the contrary, the Kinetic Impactor (KI) and Ion Beam Deflection (IBD) techniques turn into the least valued options. This difference becomes more apparent as the **importance of the assumption consisting of the asteroid size** gains greater relevance. It should be noted that these results are in line with [29], where they conclude that KI becomes the best alternative

to deflect asteroids with estimated diameters up to 250 meters (c.f. results of scenario A in [29]). In fact, for such objects, KI reaches the suggested deflection with the lowest warning time. However, as the importance of the **assumption consisting of the asteroid size** increases, our results suggest that EGT and LA become the two preferred alternatives (c.f. Figs. 8c and 8d). Once again, our results concur with those contributed in [29]. In fact, they highlighted that LA is the most effective option for larger objects despite its current low TRL. Moreover, under the assumption that EGT can remove the desired mass from the asteroid, both LA and EGT constitute the best options to deal with asteroids with estimated diameters > 300 meters.

6. Conclusions

In this paper, a combination of fuzzy logic and MCDM techniques was developed to assess four NEA deflection technologies (i.e., KI, IBD, EGT, and LA) by a set of eight criteria. This was carried out by both (fuzzy) AHP and TOPSIS algorithms. The relative weight of each criteria was calculated according to the valuable information provided by questionnaires from a group consisting of 10 highly qualified experts from renowned institutions. It should be stressed that NEA deflection techniques were among their expertise areas.

The calculation of the weights of the criteria was carried out by fuzzy AHP. In this step of the process, the judgments of the experts were involved. The most important criteria were found to be Build Time (C_1), Active deflection duration (C_2), Level of maturity (C_7), and Asteroid Composition (C_4).

Next, the four deflection technologies were compared with respect to the set of eight criteria by taking into account their relative importance as stated by the group of experts. This was carried out by fuzzy TOPSIS. As a result, KI was found to be the best choice, followed by IBD, EGT, and LA.

The robustness of our results was verified by a double sensitivity analysis. As such, the consistency regarding the judgments as provided by the group of experts and, on the other hand, the influence of an additional criterion (i.e., the **importance of the assumption consisting of the asteroid size**, as suggested by one of the experts) was discussed.

We would like to comment that the study carried out in this paper could be further extended by involving other relevant criteria, such as the influence of the ΔV parameter, or even the cost of a NEA deflection mission. Moreover, several of the experts stressed that some demonstrations of each NEA deflection technique should be conducted to provide an updated understanding of their adequacy.

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The survey results are based on the expert opinions of the participating individuals and do not necessarily reflect the official positions of their parent institutions.

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Figure 1: Graph of the membership function of the triangular fuzzy number (0.3, 0.5, 0.8).

Figure 2: Ideal alternative vs. anti-ideal alternative.

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Labels	Verbal judgments of preferences between criterion i and criterion j	Triangular fuzzy scale and reciprocals
EI	C_i is Equally Important than C_j	$(1, 1, 1)/(1, 1, 1)$
mMI/mLI	C_i is moderately More/Less Important than C_j	$(2, 3, 4)/(1/4, 1/3, 1/2)$
MI/LI	C_i is More/Less Important than C_j	$(4, 5, 6)/(1/6, 1/5, 1/4)$
MMI/MLI	C_i is Much More/Less Important than C_j	$(6, 7, 8)/(1/8, 1/7, 1/6)$
EMI/ELI	C_i is Extremely More/Less Important than C_j	$(8, 9, 9)/(1/9, 1/9, 1/8)$

Table 1: Fuzzy scale of valuations for the comparison process by pairs.

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 2: Random indices for orders of the matrix C ranging from 1 to 15 [23].

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

Table 3: The decision matrix.

E_1	$C_1 = C_2 > C_4 = C_7 = C_8 > C_6 > C_3 = C_5$
E_2	$C_1 > C_4 > C_5 > C_3 > C_2 = C_8 > C_6 > C_7$
E_3	$C_1 > C_4 > C_3 > C_2 > C_5 > C_6 > C_7 > C_8$
E_4	$C_7 = C_8 > C_1 > C_2 > C_5 = C_6 > C_4 > C_3$
E_5	$C_8 > C_7 > C_1 > C_6 > C_5 > C_4 > C_2 = C_3$
E_6	$C_1 > C_7 > C_2 > C_3 = C_4 = C_5 > C_6 = C_8$
E_7	$C_1 > C_7 = C_8 > C_4 = C_5 > C_3 = C_6 > C_2$
E_8	$C_1 > C_7 = C_8 > C_2 > C_5 > C_3 = C_4 = C_6$
E_9	$C_1 > C_4 = C_5 > C_3 > C_2 = C_7 > C_6 > C_8$
E_{10}	$C_1 > C_7 > C_2 = C_4 = C_5 = C_8 > C_3 = C_6$

Table 4: Order of importance of the criteria as provided by each expert.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
C_1	1	EI	EMI	mMI	EMI	MMI	mMI	mMI
C_2		1	EMI	mMI	EMI	MMI	mMI	mMI
C_3			1	MLI	EI	mLI	LI	LI
C_4				1	MMI	MI	EI	EI
C_5					1	mLI	LI	LI
C_6						1	mLI	mLI
C_7							1	EI
C_8								1

Table 5: Matrix of judgments as provided by the expert E_1 .

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	Criteria weights
C_1	1	1	9	3	9	7	3	3	0.2822
C_2	1	1	9	3	9	7	3	3	0.2822
C_3	1/9	1/9	1	1/7	1	1/3	1/5	1/5	0.0223
C_4	1/3	1/3	7	1	7	5	1	1	0.1279
C_5	1/9	1/9	1	1/7	1	1/3	1/5	1/5	0.0223
C_6	1/7	1/7	3	1/5	3	1	1/3	1/3	0.0425
C_7	1/3	1/3	5	1	5	3	1	1	0.1103
C_8	1/3	1/3	5	1	5	3	1	1	0.1103

Table 6: Matrix of comparisons and column of criteria weights as provided by the expert E_1 .

Criteria	Weights (fuzzy numbers)
C_1 .- Build Time	[0.253, 0.353, 0.479]
C_2 .- Active deflection duration	[0.143, 0.200, 0.276]
C_3 .- Importance of asteroid rotation	[0.044, 0.059, 0.082]
C_4 .- Importance of asteroid composition	[0.071, 0.097, 0.134]
C_5 .- Importance of asteroid structure	[0.050, 0.069, 0.099]
C_6 .- Importance of asteroid shape	[0.044, 0.060, 0.085]
C_7 .- Level of maturity	[0.071, 0.098, 0.138]
C_8 .- Mission risk	[0.047, 0.064, 0.093]

Table 7: The weights of criteria as obtained by homogeneous aggregation of the judgments of the experts.

Linguistic label L_1	Linguistic label L_2	Linguistic label L_3	Fuzzy numbers
Very Short (VS)	Little Importance (LI)	Very Low (VLo)	[0, 1, 3]
Short (S)	Moderate (Mo)	Low (Lo)	[1, 3, 5]
Medium (M)	Important (I)	Medium (M)	[3, 5, 7]
Long (L)	Very Important (VI)	High (H)	[5, 7, 9]
Very Long (VL)	Extremely Important (EI)	Very High (VH)	[7, 9, 10]

Table 8: The three sets of linguistic labels, their tags, and their associated triangular fuzzy numbers to assess all the alternatives by each attribute.

Experts (E_i)	Alternatives (A_i)	Criteria (C_i)							
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
E_1	A_1 . Kinetic Impactor (KI)	M	VS	LI	EI	VI	VI	H	M
E_2		S	VS	EI	EI	VI	VI	H	Lo
E_3		VL	VS	LI	Mo	LI	Mo	VH	VH
E_4		VS	S	LI	LI	I	Mo	H	Lo
E_5		S	M	VI	LI	VI	EI	VH	H
E_6		VS	VS	Mo	Mo	I	Mo	H	M
E_7		M	S	I	VI	VI	I	H	H
E_8		S	S	I	I	Mo	Mo	Mo	M
E_9		L	M	EI	EI	EI	EI	VH	H
E_{10}		S	VS	LI	EI	EI	Mo	VH	M
E_1	A_2 . Ion Beam Deflection (IBD)	L	L	LI	EI	LI	VI	M	VLo
E_2		L	M	VI	I	I	I	Lo	H
E_3		VS	L	VI	LI	Mo	I	M	M
E_4		VL	VL	VI	VI	Mo	Mo	VLo	VH
E_5		M	M	LI	LI	LI	LI	H	M
E_6		S	L	LI	LI	Mo	Mo	H	Lo
E_7		M	VL	LI	Mo	Mo	I	VLo	VH
E_8		M	L	LI	LI	LI	LI	Lo	H
E_9		M	S	I	I	I	EI	VH	H
E_{10}		M	L	I	I	Mo	I	M	Lo
E_1	A_3 . Enhanced Gravity Tractor (EGT)	VL	L	LI	EI	EI	Mo	VLo	VH
E_2		M	L	VI	Mo	VI	I	M	M
E_3		S	VL	Mo	LI	Mo	I	Lo	M
E_4		L	VL	LI	LI	Mo	LI	Lo	H
E_5		VL	VL	VI	LI	LI	Mo	VLo	VH
E_6		L	VL	LI	LI	LI	LI	Lo	Lo
E_7		M	VL	LI	LI	LI	I	Lo	H
E_8		M	M	Mo	I	LI	LI	Lo	H
E_9		L	L	I	I	I	I	VH	H
E_{10}		VL	VL	LI	Mo	Mo	LI	Lo	Lo
E_1	A_4 . Laser Ablation (LA)	VL	M	Mo	EI	VI	Mo	VLo	H
E_2		L	M	VI	EI	I	I	Lo	M
E_3		S	M	VI	VI	VI	EI	VLo	Lo
E_4		VL	VL	VI	VI	I	Mo	VLo	VH
E_5		VL	VL	EI	EI	Mo	LI	VLo	M
E_6		L	M	EI	EI	VI	Mo	Lo	H
E_7		M	VL	Mo	Mo	Mo	I	VLo	VH
E_8		L	M	LI	LI	LI	LI	VLo	H
E_9		M	S	I	VI	VI	EI	VH	H
E_{10}		VL	L	I	I	Mo	I	Lo	Lo

Table 9: Our decision matrix.

	Fuzzy Numbers	Defuzzification process	Ranking
A_1	[0.214, 0.778, 2.808]	A_1 3.07	1
A_2	[0.129, 0.471, 1.681]	A_2 1.85	2
A_3	[0.070, 0.280, 1.119]	A_3 1.16	3
A_4	[0.059, 0.194, 0.642]	A_4 0.74	4

Table 10: Ranking of the alternatives by crisp (real) numbers. This was obtained through FTOPSIS methodology.

Alternatives	Weights provided by group of experts (Table 7)		All the criteria with the same weight	
	R_i	Ranking	R_i	Ranking
A_1 . Kinetic Impactor (KI)	3.07	1	1.93	1
A_2 . Ion Beam Deflection (IBD)	1.85	2	1.80	2
A_3 . Enhanced Gravity Tractor (EGT)	1.16	3	1.61	3
A_4 . Laser Ablation (LA)	0.74	4	0.66	4

Table 11: Ranking comparison: weights as provided by the group of experts vs. equally weighted criteria.

Alternatives	Importance of asteroid size
A_1 . Kinetic Impactor (KI)	Very High (VH)
A_2 . Ion Beam Deflection (IBD)	Very High (VH)
A_3 . Enhanced Gravity Tractor (EGT)	Very Low (VLo)
A_4 . Laser Ablation (LA)	Low (Lo)

Table 12: Importance of the asteroid size for each NEA deflection alternative.

Importance of asteroid size = 10% relevance with the remaining criteria proportionally weighted			Importance of asteroid size = 20% relevance with the remaining criteria proportionally weighted		
Alternatives	R_i	Ranking	R_i	Ranking	
A_1 . Kinetic Impactor (KI)	2.34	1	1.65	2	
A_2 . Ion Beam Deflection (IBD)	1.50	2	1.04	4	
A_3 . Enhanced Gravity Tractor (EGT)	1.36	3	1.75	1	
A_4 . Laser Ablation (LA)	1.06	4	1.49	3	
Importance of asteroid size = 25% relevance with the remaining criteria proportionally weighted			Importance of asteroid size = 50% relevance with the remaining criteria proportionally weighted		
Alternatives	R_i	Ranking	R_i	Ranking	
A_1 . Kinetic Impactor (KI)	1.40	3	0.63	3	
A_2 . Ion Beam Deflection (IBD)	0.87	4	0.36	4	
A_3 . Enhanced Gravity Tractor (EGT)	1.92	1	2.51	1	
A_4 . Laser Ablation (LA)	1.66	2	2.14	2	

Table 13: Analysis of the influence of the importance of the assumption consisting of the asteroid size in the ranking of the alternatives (crisp numbers).

Declaration of interests

- ☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
- ☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: