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Comparative analysis of redirection methods for asteroid resource exploitation

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ABSTRACT

An in-depth analysis and systematic comparison of asteroid redirection methods are performed within a resource exploitation framework using different assessment mechanisms. Through this framework, mission objectives and constraints are specified for the redirection of an asteroid from a near-Earth orbit to a stable orbit in the Earth–Moon system. The paper provides a detailed investigation of five redirection methods, i.e., ion beam, tugboat, gravity tractor, laser sublimation, and mass ejector, with respect to their capabilities for a redirection mission. A set of mission level criteria are utilized to assess the performance of each redirection method, and the means of assigning attributes to each criterion is discussed in detail. In addition, the uncertainty in physical characteristics of the asteroid population is quantified through the use of Monte Carlo analysis. The Monte Carlo simulation provides insight into the performance robustness of the redirection methods with respect to the targeted asteroid range. Lastly, the attributes for each redirection method are aggregated using three different multicriteria assessment approaches, i.e., the Analytical Hierarchy Process, a utility-based approach, and a fuzzy aggregation mechanism. The results of each assessment approach as well as recommendations for further studies are discussed in detail.

1. Introduction

Asteroids are small celestial bodies that have great potentials to provide insight into the nature of the early solar system, expedite human space activities, as well as cause incredible devastation to Earth through an impact. The incentives for investigating asteroids are numerous and varied, and both the public and private sectors have recently taken interest. In particular, NASA currently has three programs focused on asteroids: OSIRIS-REx, [1] Robotic Asteroid Prospector [2] and the Asteroid Redirect Mission [3]. Further, JAXA's Hayabusa mission to collect samples from Itokawa [4] as well as ESA's Rosetta mission to explore 67P/Churyumov–Gerasimenko [5] were historical steps towards the ultimate goal of exploiting and utilizing resources of celestial bodies in our solar system. Moreover, several private corporations are seeking means to profitably exploit asteroid resources [6]. Now, more than ever, a systematic assessment of asteroid redirection methods is of value, particularly with respect to resource exploitation.

The vast majority of current research into asteroids investigates the deflection of large asteroids over long time periods. Contrastingly, this paper focuses on the redirection of asteroids from a near-Earth orbit, i.e., orbits with a perihelion distance less than 1.3 Astronomical Unit (AU), to a stable and easily accessible orbit in the Earth–Moon system (EMS) for the purpose of resource exploitation. This work will investigate methods primarily studied for

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asteroid deflection within the context of a redirection and exploitation framework, and will expand upon previous work in [7]. The following sections outline the major mission constraints, the assessment criteria, the redirection methods considered, and the selected assessment approaches. Lastly, the performance of each redirection method with regard to the various criteria and assessment approaches will be discussed in detail in light of the quantified results.

2. Problem formulation

The scope of an asteroid redirection mission for resource exploitation provides clear constraints on both the target range of asteroids and on the employable redirection methods. In particular, the asteroid population considered will be constrained with respect to taxonomic type, density, capture delta-v, diameter, and spin rate. Since the goal is to redirect the asteroid for resource exploitation, the target asteroids will be restricted to the most suitable taxonomic types, i.e., carbonaceous (C-Type) and metallic (M-Type) asteroids. C-Type asteroids contain volatile materials useful for the production of propellants and supporting life support systems. Moreover, M-Type asteroids contain high concentrations of metals for in-situ construction. Given the taxonomic types, the range of asteroid densities considered reflect a Gaussian distribution about the calculated average densities for each type, namely, 1380 kg/m^3 and 5320 kg/m^3 for C-Type and M-Type asteroid, respectively [8]. The asteroid diameters are also constrained to a range of small to medium size asteroids between 20 m and 150 m in diameter. The upper limit is set to represent the largest diameter considered safe with regard to planetary protection. In particular, a near-Earth asteroid (NEA) with a diameter greater than 150 m and a minimum orbital intersection distance less than 0.05 AU is termed a potentially hazardous object (PHO) [9]. Moreover, the lower limit of 20 m represents a bound for the smallest asteroids considered economically valuable, and also eliminates the prospect of utilizing envelopment redirection methods that are viable for very small diameter asteroids [2,10]. The spin rate of the asteroids is also of particular importance for asteroid redirection, and is seen to have considerable variability especially with regard to small asteroids [11]. The spin rate has also been shown to be related to asteroid diameter [11], and as a result, will be constrained relative to the selected diameter according to a relation described in Section 3.1.

The redirection methods considered are also constrained with regard to number of spacecraft, system mass, system volume, timeframe for redirection, and Technology Readiness Level (TRL) in order to ensure their viability for a redirection mission and to provide a valid baseline for comparison. Although several redirection methods have been considered with respect to formation design [12], this assessment focuses on the simplest practical spacecraft configuration for each method, namely consisting of one or two spacecraft systems. The maximum mass and volume for the system will also be constrained to the payload specifications of an Atlas V launch vehicle. Each redirection method will have a system mass less than 6800 kg and stowed system volume less than a payload envelope of 4.572 m in diameter and 12.192 m in length [13]. The redirection timeframe will also be constrained to 4 years from rendezvous to capture in order to ensure economic feasibility [14]. Lastly, the redirection method will have a minimum of TRL 2, i.e. “Technology concept and/or application formulated” [15]. The restriction of the Technology Readiness Level guarantees the redirection methods considered have been sufficiently researched, such that attributes can be readily assigned to the assessment criteria.

In addition, the mission design assumes a simple circular capture orbit, and focuses on the redirection methods applicability from rendezvous to capture. It should be noted that this work considers monolithic asteroids, and does not study rubble-pile or highly porous asteroid structures. Lastly, since the orbital paths of the target asteroids are intersecting or closely approaching the Earth's orbit, the Earth's orbital path is taken as a reference for defining the environmental constraints. The environmental constraints imposed on the asteroids and redirection techniques are standard values, and as such all redirection methods are assumed to satisfy these constraints.

3. Assessment criteria

The assessment criteria represent a combination of standard mission parameters and criteria specific to an asteroid redirection mission. The criteria are defined in Table 1, and a detailed methodology for each criterion is provided in the subsequent sections. It is important to note that mass and volume have been omitted from the assessment criteria. As it will be seen in Section 4, all the redirection methods benefit from maximizing the system mass to the constrained upper bound, and as a result comparing the mass would be inconsequential. Further, since the mass is maximized, there is very little value in comparing system volume. The advantage of a smaller stowed configuration would normally imply additional payload capacity; however, in this case payload limits have already been reached. The selected criteria are most valuable in assessing an asteroid redirection mission from the perspective of economic viability and performance efficacy.

A discussion of the method for assigning attributes to each criterion is discussed for delta-v, performance robustness, asteroid alteration, system cost, technology readiness and risk, mission risk, and long-term value. The average required power will be determined directly from the redirection method specifications in Section 4.

3.1. Delta-v, performance robustness and asteroid alteration

The delta-v for each redirection method is determined through the method's specific formulae that will be presented in Section 4. The formulae for calculating delta-v are included in the Monte Carlo simulation, since they are

Table 1
Assessment criteria.

ID[a]	Criteria	Description	Metric
CR-1	Delta-v	The change in velocity the system is able to enact on the asteroid over the specified time interval; where greater delta-v is preferred.	km/s
CR-2	Performance robustness	The ability of the system to resist change, particularly variation in asteroid parameters, where greater robustness is preferred. Robustness with respect to chemical composition, geometry, diameter, density, and rotation rate will be considered.	Coefficient of variation of the delta-v found through Monte Carlo analysis
CR-3	Asteroid alteration	The change in asteroid mass that results from the redirection method from rendezvous to capture; where less alteration is preferred.	Average mass change from rendezvous to capture found through Monte Carlo analysis
CR-4	System cost	This is defined as the system cost for the redirection method, from development to completion; where lower system cost is preferred.	USD
CR-5	Average required power	The average electrical power required for operation of the redirection method; where less required power is preferred.	W
CR-6	Technology readiness and risk	The technological readiness and risk assessment (TRRA) value will consider the technology readiness level, the research and development degree of difficulty (R&D^3), and the technology need value for the redirection method; where a lower integrated technological risk is preferred.	Integrated technology risk matrix
CR-7	Mission risk	This is defined as any risk that may jeopardize the implementation or success of the mission; where less mission risk is preferred.	Risk assessment table
CR-8	Long-term value	The value of the redirection method over an extended period of time with consideration of *extensibility* and *reusability*; where greater long-term value is preferred.	Aggregation of long-term value parameters

[a] Note that each criterion is given an identification code CR – ; where CR signifies that the parameter is a criterion, and the represents the criterion's number.

Table 2
Monte Carlo parameters and distributions.

Category	Parameter	Range	Distribution	Fig.
Average diameter	d_{ast}	20–150 m	Power law distribution [17]	1a
Period of rotation	T_{ast}	See Eq. (2) for more details (μ_T=11.85 ± 0.09 h)	Exponential distribution estimated from [18]	1b
Density	ρ_{ast}	1380 ± 20 kg/m^3 (C-Type) 5320 ± 70 kg/m^3 (M-Type)	Gaussian distribution for each type [8]	–
Enthalpy of sublimation	E_{sub}	2.75×10^5–1.9686×10^7 J/kg	GCDF determined from Ref. [19]	1c
Temp. of sublimation	T_{sub}	1700–812 K	GCDF determined from Ref. [19]	1d
Specific heat	c_a	375–750 J/kg K	GCDF determined from Ref. [19]	1e
Thermal conductivity	k_a	0.2–2 W/m K	GCDF determined from Ref. [19]	1f

dependent upon uncertain asteroid parameters. The average delta-v, $\mu_{\Delta v}$, and standard deviation of delta-v, $\sigma_{\Delta v}$, will be found for the target population of asteroids, and subsequently used for the assessment of the performance robustness. To determine the robustness of the redirection method, the coefficient of variation, c_v, will be calculated from Eq. (1).

$$c_v = \frac{\sigma_{\Delta v}}{\mu_{\Delta v}} \tag{1}$$

The developed Monte Carlo simulation utilizes both theoretically and experimentally derived distributions of asteroid parameters to provide insight into the performance of the redirection methods with respect to the actual NEA population. The Monte Carlo analysis randomly generates asteroid values, and completes 10,000 evaluations to ensure the robustness of the calculated results. It should be noted that not all asteroid parameters affect the performance of each redirection method. The asteroid parameters are generated in the simulation according to the distributions specified in Table 2, and include diameter, period of rotation, density, enthalpy of sublimation, temperature of sublimation, specific heat, and thermal conductivity (Fig. 1). The assessment equally generates M-Type and C-Type asteroids, since they are considered, for the purpose of this evaluation, equally suitable redirection targets. Generally, the albedo of a C-Type asteroid is expected to range from 0.03 to 0.09, whereas for an M-Type asteroid the albedo is much brighter from 0.10 to 0.18 [16]. In this investigation, mid-range values of 0.05 and 0.15 are utilized to represent the albedos of the carbonaceous and metallic types, respectively. In addition, the period of rotation follows a dependent distribution based on the selected asteroid diameter. This relationship, correlated from asteroid data in a previous study [7], can be described by Eq. (2), where T_{ast} is the period of rotation and H is the absolute magnitude of the asteroid.

$$T_{ast} = e^{-0.5091H + 11.32} \tag{2}$$

The asteroid alteration criterion will be assessed through the utilization of a mass-loss ratio that relates the mass removed from the asteroid to the initial mass of the asteroid. The Monte Carlo simulation will output the amount of mass lost through the utilization of the redirection method as well as the initial mass of the asteroid. Eq. (3) describes the mass-loss ratio, $M_r(\%)$, which

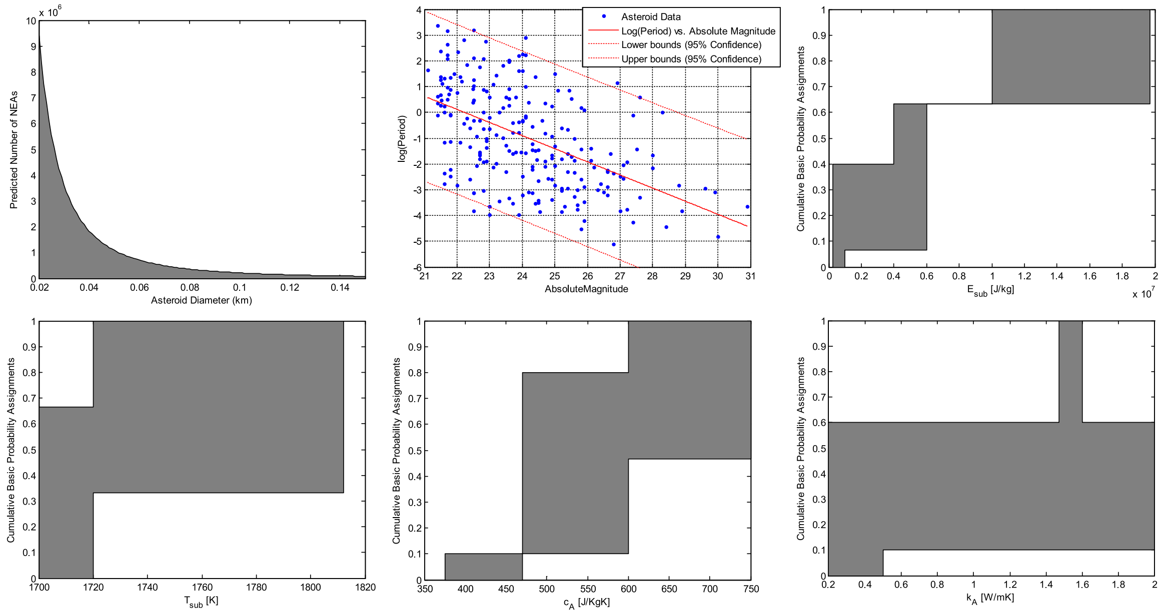


Fig. 1. Monte Carlo parameter distributions, i.e., power-law distribution of NEA diameters [17] (top left-1a); asteroid period versus absolute magnitude data [18] with line of best fit and 95% confidence intervals (top center-1b); GCDF of asteroid enthalpy of sublimation determined from [19] (top right-1c); GCDF of asteroid temperature of sublimation determined from [19] (bottom left-1d); GCDF of specific heat determined from [19] (bottom center-1e); and GCDF of asteroid thermal conductivity determined from [19] (bottom right-1f).

Table 3
QuickCost parameter definitions in FY2010 Dollars [20].

Parameter	Definition
Dry Mass	Dry mass of spacecraft bus and instruments in kg
Power	LEO equivalent beginning of life power (BOLP) in watts
Data%	Data rate percentile (fraction) relative to the state-of-the-art at authority to proceed (ATP) (enter 0.5 for median data rate missions, <0.5 for lower data rates, >0.5 for higher data rates)
Life	Advertised Design Life (in months) – advertised design life excluding extended operations
New	Percent new (fraction): 0.2–0.3 = Simple Mod, 0.3–0.7 Extensive Mod, 0.7–1.0 = New, >1.0 for New Technology
Planetary	0 for earth orbital, 1 for planetary (yes or no)
Year	ATP date in 4 digit calendar year minus 1960
InstrComp%	Instrument complexity percentile (fraction) – relative to "average" instrument complexity (enter 0.5 for median complexity, <0.5 for lower complexity, >0.5 for higher complexity)
Team	Team experience: 1 = unfamiliar, 2 = mixed, 3 = normal, 4 = extensive

normalizes the change in mass, Δm, by expressing it as a percentage of the initial asteroid mass, M_{ast}.

$$M_r(\%) = \frac{\Delta m}{M_{ast}} \tag{3}$$

It is important to note that the mass-loss ratio will only be calculated for methods that directly affect the mass of the asteroid through the ejection or sublimation of asteroid material.

3.2. System cost

The system cost-criteria is an estimate of the mission cost utilizing the NASA single-Cost-Estimating-Relationship (CER) QuickCost model. The model utilizes relationships between key mission parameters to estimate the cost of the mission. The mission design parameters are constant with respect to data rate percentile, team experience level, mission type (i.e., planetary), authority to proceed date, and mission lifetime for all the redirection methods. (See Table 3 [20] for descriptions.) The QuickCost model is considered as a conservative estimating tool, and can be calculated using Eq. (4) for calendar year 2010 US Dollars, with the mission parameters outlined in Table 3. The total system cost includes an additional 5% for each year of mission operations required, as well as \$250M for the launch of an Atlas V. [20]

$$\begin{aligned} Y = 2.829 &\times \left(\mathrm{DryMass}^{0.457}\right) \times \left(\mathrm{Power}^{0.157}\right) \\ &\times \left(2.718^{(0.171\times \mathrm{Data\%})}\right) \times \left(2.718^{(0.00209\times \mathrm{Life})}\right) \\ &\times \left(2.718^{(1.52\times \mathrm{New})}\right) \times \left(2.718^{(0.258\times \mathrm{Planetary})}\right) \\ &\times \frac{1}{2.718^{(0.0145\times(\mathrm{Year}-1960))}} \times \left(2.718^{(0.467\times \mathrm{InstrComp\%})}\right) \\ &\times \frac{1}{\left(2.718^{(0.237\times \mathrm{Team})}\right)} \end{aligned} \tag{4}$$

Table 4
Standard technology readiness level definitions [21,22].

TRL	Definition	Explanation
TRL 1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.
TRL 2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented and R&D started. Applications are speculative and may be unproven.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept	Active research and development is initiated, including analytical/laboratory studies to validate predictions regarding the technology.
TRL 4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together.
TRL 5	Component and/or breadboard validation in relevant environment	The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
TRL 6	System/subsystem model or proto-type demonstration in a relevant environment (ground or space)	A representative model or prototype system is tested in a relevant environment.
TRL 7	System prototype demonstration in a space environment	A prototype system that is near, or at, the planned operational system.
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)	In an actual system, the technology has been proven to work in its final form and under expected conditions.
TRL 9	Actual system “flight proven” through successful mission operations	The system incorporating the new technology in its final form has been used under actual mission conditions.

Table 5
Research and development degree of difficulty scale [21].

R&D^3	Definition
R&D^3=1	**Very low degree of difficulty anticipated in achieving research and development objectives for this innovation;** only one (or at most two) short-duration technological approach(es) needed to be assured of a high probability of success in achieving technical objectives in later systems applications
R&D^3=2	**Moderate degree of difficulty anticipated in achieving R&D objectives for this innovation;** 2 or 3 technological approaches needed; conducted early to allow an alternatives to be pursued to assure of a high probability of success in achieving technical objectives in later systems applications
R&D^3=3	**High degree of difficulty anticipated in achieving R&D objectives for this innovation;** 3 to 4 technological approaches needed; conducted early to allow an alternate subsystem approach to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications
R&D^3=4	**Very high degree of difficulty anticipated in achieving R&D objectives for this innovation;** 4 to 5 or more technological approaches needed; conducted early to allow an alternate system concept to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications
R&D^3=5	**The degree of difficulty anticipated in achieving R&D objectives for this innovation is so high that a fundamental breakthrough in physics or chemistry/etc. is needed;** basic research in key areas needed before feasible system concepts can be refined

3.3. Technological readiness and risk assessment

An integrated technological readiness and risk assessment (TRRA) quantifies the maturity of the critical technologies for each redirection method as well as the potential risk of not meeting development expectations during the research and development process. The integrated TRRA was developed in [21] for the assessment of space missions, involving the aggregation of three parameters, i.e., technology readiness level (TRL), research and development degree of difficulty (R&D^3), and technology need value (TNV). Through an evaluation of the major technological components specific to each redirection, method an understanding of their technological maturity and risk can be established. The three most critical technological components to mission success for each method will be investigated.

The technology readiness level represents a standardized scale developed by NASA to evaluate the maturity of a technology as applied to a particular task. A set of definitions and explanations for each TRL is provided in Table 4. In this assessment, the Δ-TRL will be utilized to measure the difference between the current readiness level of a technology and the desired TRL at the commencement of the R&D process. This measure is valuable in expressing the levels of development maturity between the current state of the redirection method and the desired maturity. The desired TRL for the redirection methods in this assessment is TRL 6, i.e., system/subsystem model is demonstrated in a relevant environment, such that the redirection method will become ready for demonstration in a *space* environment at the next level.

The research and development degree of difficulty is a measure of the expected effort and probability of success in the development process. The R&D^3 scale described in Table 5 [21] is related to TRL, in that it aims to quantify the effort required to bring the technology to maturity. Further, there is usually an inversely proportional relationship between TRL and R&D^3, i.e., low TRL suggests high R&D^3 and high TRL suggests low R&D^3. However, it should be noted that there are cases where this relationship does not hold, since R&D^3 path is not dependent on TRL, and a technology with a high (or low) TRL may have a simple (or complicated) development process.

The technologies utilized by the redirection methods can be considered as either being critical to the functionality of

Table 6
Technology need value scale [23].

TNV	Weighting (%)	Definition
TNV-1	40	The technology effort is not critical at this time to the success of the program – the advances to be achieved are useful for some cost improvements; however, the information to be provided is not needed for management decisions until the far-term
TNV-2	60	The technology effort is useful to the success of the program – the advances to be achieved would meaningfully improve cost and/or performance; however, the information to be provided is not needed for management decisions until the mid- to far-term.
TNV-3	80	The technology effort is important to the success of the program – the advances to be achieved are important for performance and/or cost objectives and the information to be provided is needed for management decisions in the near- to mid-term.
TNV-4	100	The technology effort is very important to the success of the program; the advances to be achieved are enabling for cost goals and/ or important for performance objectives and the information to be provided would be highly valuable for near-term management decisions.
TNV-5	120	The technology effort is critically important to the success of the program at present; the performance advances to be achieved are enabling and the information to be provided is essential for near-term management decisions.

the system or beneficial to the success of the method given a redirection mission. The significance of the technology to the redirection method being developed can be assessed using a technology need value scale, see Table 6. The less critical a technology is to the overall success of the system, the more readily it can be replaced, removed, or modified with other technologies. The TNV is a method for characterizing the importance of a technology to the mission success, and can be equated to a "consequence" value in a standard risk assessment matrix [23].

The method for aggregating TRL, R&D^3, and TNV utilizes an integrated technological risk matrix, where the likelihood of R&D failure, $L_{R\&D}$, is equal to the R&D^3 value (Eq. (5)), and the consequence of R&D failure, $C_{R\&D}$, can be determined from Eq. (6) for the ith technology considered [23] using Δ[TRL] with [TNV] as a weighting factor.

$$L_{R\&Di} \approx \left[\mathrm{R\&D}^3\right]_i \tag{5}$$

$$C_{R\&Di} \approx [\mathrm{TNV}]_i \times \Delta[\mathrm{TRL}]_i \tag{6}$$

An integrated TRRA value, I_{TRRA}, is obtained for the primary technologies of each redirection method through Eq. (7) that sums the product of the likelihood and consequence values for each technology. Fig. 2 depicts a standard fever chart for plotting likelihood and consequence values.

$$I_{TRRA} = \sum_{i=1}^{n} C_{R\&Di} \times L_{R\&Di} \tag{7}$$

3.4. Mission risk

The mission risk is assessed separately from the technological readiness and risk assessment in order to identify any mission specific risks that arise from the particular redirection method. The risk assessment method utilized in this paper is based on models from New SMAD [20] and the Goddard Risk Matrix Standard Scale [24]. Table 7 outlines the scales for event likelihood and consequence evaluation, similar to the likelihood and consequence values found in the TRRA section. A general risk matrix objective quantification formula, Eq. (8), is applied to the likelihood and consequence values to determine the overall expected percentage of mission objectives achieved, $E_{MR}(\%)$, for the primary technologies of each redirection method. [20]

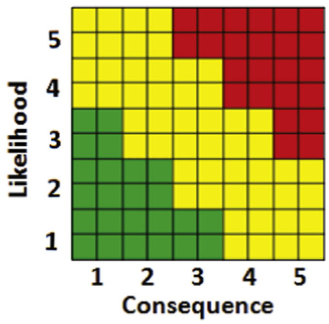


Fig. 2. Risk matrix based on NASA standards [20, 23, 24].

$$E_{MR}(\%) = 1 - \sum_{i=1}^{n} C_{MRi} \times L_{MRi} \tag{8}$$

3.5. Long-term value

The long-term value of each redirection method is dependent on two key parameters, i.e., system extensibility and reusability. The system extensibility refers to the ability of the system to be extended for future missions, including missions with different primary goals, whereas reusability refers to the ability of the system to be extended for future asteroid redirection missions. The system extensibility and reusability have been defined using a qualitative scale, shown in Table 8, and the assigned values for each redirection method will be averaged to determine the method's long-term value attributes.

4. Redirection methods

This section summarizes the main redirection methods discussed in the literature, and provides a brief description

Table 7
Mission risk likelihood and consequence scales (adapted from Table 24–11 in Ref. [20]).

	1 – Very low	**2 – Low**	**3 – Moderate**	**4 – High**	**5-Very high**
Estimated likelihood of not meeting mission objectives	$P_T \leq 2\%$	$P_T \leq 15\%$	$P_T \leq 25\%$	$P_T \leq 50\%$	$P_T > 50\%$
Consequence scale	Minimal (1%) loss of mission objectives	Small (10%) loss of mission objectives	Moderate (50%) loss of mission objectives	Significant (90%) loss of mission objectives	Mission failure (100% loss of mission objectives)

Table 8
Long-term value assessment scale.

Long-term value	**1 – Very low**	**2 – Low**	**3 – Moderate**	**4 – High**	**5-Very high**
System extensibility	No extensibility of system	Minor extensibility of redirection system	Moderate extensibility of redirection system. Extended mission achievable with major modification	Major extensibility of redirection system. Extended mission achievable with minor modification	Major extensibility of redirection system. Extended mission achievable with no modification
Reusability	Secondary mission not achievable	Secondary mission achievable with major modification	Secondary mission achievable with moderate modification	Secondary mission achievable with minor modification	Secondary mission achievable with no modification

of each. A more detailed description of each considered technique will be presented within the context of the criteria prescribed previously. The following sections represent the key methods to be considered in this work. There are several other deflection methods that are not suitable for a redirection mission; for a discussion of these methods and a rationale for their omission, please refer to [7].

4.1. Ion beam

The ion beam method is a free-flying approach that utilizes a hovering spacecraft that uses an ion beam to create a thrusting force on the asteroid. Since the asteroid gravitational field applies a minimal force on the spacecraft, a secondary thruster that exerts a similar amount of thrust is required for station-keeping. At a hovering distance of approximately twice the asteroid diameter the gravitational force of the asteroid is negligible and as such has been omitted from this analysis for simplicity [25]. The ion beam method benefits from maximizing the spacecraft mass to 6800 kg, with a structural mass of 300 kg. Previous studies have shown that the volume and TRL constraints are also satisfied given this maximization; further, the satisfaction of the volume and TRL constraints of each redirection method considered can be found in [7]. The remaining mass, 6500 kg, is allocated to the combination of fuel and power plant. The equations for fuel mass, m_{fuel}, (Eq. (9)) and power plant mass, m_{pp}, (Eq. (10)) can be rearranged to find the force of the thrusters over the prescribed time period and known thruster type (Eq. (11)) [26].

$$m_{fuel} = \frac{2F_{th}\Delta t}{v_E} \tag{9}$$

$$m_{pp} = \frac{2F_{th}\alpha v_E}{2\eta} \tag{10}$$

$$F_{th} = \frac{(m_{IBS} - m_{str})}{2\left(\frac{\Delta t}{v_e} + \frac{\alpha V_E}{2\eta}\right)} \tag{11}$$

where Δt is the timeframe for redirection, F_{th} is the force of the thruster on the asteroid, α is the inverse specific power (kg/W), η is the thruster efficiency, and v_e is the ejection velocity of the thruster. As in previous work, a conservative thruster design modeled after the RIT-XT has been utilized with a nominal power of 5 kW, nominal specific impulse of 4500 s, thruster efficiency of 60% and inverse specific power of 10 kg/kW [12]. In order to provide a consistent comparison, this thruster has also been applied to the gravity tractor and tugboat methods. The following relationship is used to determine the ejection velocity, v_e, given the assumed gravitational field of the asteroid (Eq. (12)) [25].

$$v_e = I_{sp} g \tag{12}$$

where g is the gravitational acceleration at sea-level, G is the gravitational constant, and I_{sp} is specific impulse. Lastly, the delta-v for the ion beam method can be evaluated using Eq. (13) [25].

$$\Delta V = \frac{3F_{th}\Delta t}{\rho_{ast} d_{ast}^3} \tag{13}$$

where ρ_{ast} is the asteroid density and d_{ast} is the asteroid diameter.

4.2. Tugboat

The tugboat method utilizes one or more lander spacecraft to provide a continuous thrust after attaching to the asteroid surface. This method is frequently considered for formation design, due to the complications that are associated with asteroid rotation and a lander spacecraft [12]. In single spacecraft studies, there are two typical approaches to redirection, i.e., landing on the equator with intermittent thrusting dependent on asteroid rotation [27], or landing on the spin axis and thrusting to align the spin axis with the redirection vector such that continuous thrust can be applied [28]. While a single spacecraft is the simplest configuration for the other methods considered in this paper, using two thruster spacecraft that land antipodally on the equator greatly simplifies the approach. Through the use of the two spacecraft with gimballed thrusters the tugboat method is capable of exerting continuous thrust along the redirection vector. As such, this paper considers two thrusters with a combined mass of 6800 kg. The structural mass is taken to be 500 kg, which is greater than that of the ion beam method, in order to accommodate the additional structural mass of two thruster spacecraft and two landing systems modeled after the Philae lander [29,30]. The force of the two thrusters can be found by multiplying Eq. (11) by a factor of two, and delta-v can be evaluated accordingly using Eq. (13). Lastly, it should be noted that with the two spacecraft approach the tugboat method will exhibit redundancy, and in the event of a failed landing is still capable of completing its mission with reduced thrusting force.

4.3. Gravity tractor

The gravity tractor approach utilizes the gravitational attraction between the asteroid and a hovering spacecraft to generate a redirecting force on the asteroid. The gravity tractor method has been considered for both singular and multiple spacecraft configurations [12]; however, in this paper a single large gravity tractor will be employed. In the literature, the total mass of the gravity tractor is large to maximize the gravitational force it can exert on the asteroid. As such, the gravity tractor is taken to have a mass of 6800 kg. The gravity tractor employs two angled thrusters to maintain a constant hovering distance from the asteroid. The thrusters are offset by 20°, half the angle of the exhaust cone, φ, to ensure the thruster plume does not counteract the gravitational effect by impacting the asteroid surface [31,32]. The thrust required to maintain a hover distance of approximately 1.5 times the asteroid radius from the asteroid center of mass [31] is found by equating Eqs. (14) and (15) from [32].

$$F_{hover} = T\cos\left(\sin^{-1}\left(\frac{r}{d}\right)+\varphi\right) \tag{14}$$

$$F_g = \frac{GMm_{GT}}{d^2} \tag{15}$$

where F_{hover} is the spacecraft's thrusting force in the direction of the asteroid, F_g is the gravitational force, T is the total thrust, r is the mean asteroid radius, d is the hovering distance, m_{GT} is the mass of the gravity tractor, M is the mass of the asteroid, and G is the universal gravitational constant. The gravitational acceleration induced by the spacecraft can be optimized by adjusting the hover distance with the decreasing spacecraft mass. However, for simplicity, in this analysis the hover distance is constant and the mass loss over time is described by Eq. (16) [32].

$$m_{GT}(t) = m_i e^{-\left(\frac{GM(t-t_0)}{d^2\cos\left(\sin^{-1}\left(\frac{r}{d}\right)+\varphi\right)I_{sp}g_0}\right)} \tag{16}$$

where m_i is the initial spacecraft mass, I_{sp} is the specific impulse, g_o is the gravity at the sea level, and t represents the operation time. The acceleration the gravity tractor generates with respect to the asteroid can be described by Eq. (17).

$$a_{gtug}(t) = \frac{Gm(t)}{d^2} \tag{17}$$

The induced acceleration can then be integrated with respect to the redirection timeframe to determine the total delta-v induced by the gravity tractor on the asteroid.

4.4. Laser sublimation

This redirection method employs a laser for the sublimation of the asteroid surface material in order to generate an ejecta plume. The ejecta plume generates a thrust on the asteroid and induces a change in velocity. The laser sublimation approach has been studied extensively for asteroid deflection, and several formation strategies have been proposed [33]. This paper utilizes the AdAM/LightTouch2 model as a reference design [34], and extrapolates the laser systems to maximize the spacecraft parameters within the given mission constraints. The laser sublimation spacecraft will have a total mass of 6800 kg, with a 16 kW power system with an allocated mass of 1700 kg [34]. Since the laser sublimation approach generates thrust through ablation of the surface material, it is important to evaluate the mass flow rate of the sublimated material, $\dot{m}$; described in Eq. (18) below [35].

$$\dot{m} = 2V_{ROT}\int_{y_{min}}^{y_{max}}\int_{t_{in}}^{t_{out}} \frac{1}{\left(E_v+\frac{1}{2}\bar{v}^2+C_p(T_{sub}-T_0)+C_v(T_{sub}-T_0)\right)}(P_I-Q_{RAD}-Q_{COND})dydt \tag{18}$$

where V_{ROT} is the velocity of the asteroid as it travels through the illuminated spot area, E_v is the latent heat of complete sublimation, $[y_{min}, y_{max}]$ defines the height of the spot, $[t_{in}, t_{out}]$ is the duration for which the spot is illuminated, $_{PI}$ is the absorbed laser power per unit area, Q_{RAD} is the heat loss per unit area through radiation, Q_{COND} is the heat loss per unit area through conduction, $\bar{v}$ is the ejecta velocity, C_p and C_v are the heat capacities, T_{sub} is the sublimation temperature, and T_0 is the temperature of the material prior to sublimation. Although several studies investigate the degradation of the absorbed laser power due to re-condensed ejecta material [19,35], this work does not consider this effect in the mass flow rate analysis. However, in order to account for the effects of degradation this factor has been included in the mission risk assessment.

In order to assess the mass flow rate, we must first define the amount of laser power absorbed by the asteroid surface. The absorbed power equation utilized, shown in Eq. (19), accounts for the efficiency of the laser system, η_L, the input power to the laser, P_{IN}, the absorption of the laser beam within the plume, τ_g, the area of the spot, A_{spot}, and the absorption at the spot $\alpha_m = (1-\varepsilon_a\alpha_s)$, which is dependent on the albedo, α_s, of the asteroid and the increment in reflectivity, ε_a, at the frequency of the laser beam [34].

$$P_I = \frac{\tau\tau_g\alpha_m\eta_L P_{IN}}{A_{spot}} \tag{19}$$

The laser efficiency was taken to be 50% [19], and the absorption of the laser beam within the plume was conservatively chosen at 10% with a spot size of 1 mm [35]. For more information regarding the average velocity of the ejecta plume as well as the radiative and conductive heat loss, refer to [35]. The following equation outlines the delta-v induced by sublimation, where F_{sub} is the sublimation force, $m_A(t)$ is the time dependent mass of the asteroid, and $[t_f, t_i]$ denotes the integral over the redirection timeframe [34].

$$\Delta V = \int_{t_i}^{t_f} \frac{F_{sub}}{m_A(t)} dt \tag{20}$$

Eq. (21) describes the calculation for the force of sublimation [35],

$$F_{sub} = \lambda \bar{v} \dot{m} \tag{21}$$

where $\dot{m}$ is the mass flow rate, $\bar{v}$ is the ejecta average velocity, and λ is the scatter factor ($\lambda = 2/\pi$, which represents a uniform distribution over a half sphere.)

4.5. Mass ejector

This method removes asteroid materials and ejects them to create a thrust. The mass ejector utilizes a drilling or coring mechanism on the asteroid surface, and then ejects the removed mass with a rail gun. For a single mass ejector spacecraft, the typical strategy is to land on the equator of the asteroid and periodically launch asteroid material in line with the redirection vector. Similar to the previous studies [7], the mass ejector model uses the Modular Asteroid Deflection Mission Ejector Node (MADMEN) concept as a baseline for design specifications [36]. The specifications of this mass ejector spacecraft have been modified from the MADMEN concept given the increased mass of 6800 kg. The base diameter of the spacecraft is taken at 4.5 m with a deployable rail length of 15 m. Moreover, the mass of the power system is taken to be approximately 30% of the dry mass [36]. The nominal power required is 20 kW, and with a rail gun energy efficiency of 30%, the power converted to kinetic energy, P_k, can be obtained through Eq. (22) [32].

$$P_k = 0.3\,\frac{m_{power}}{\tau} \tag{22}$$

where τ is the mass-to-power ratio taken as an average of power systems to be 25 kg/kW [32]. Eq. (23) shows the mass ejected with each shot, m_{launch}, can be expressed in terms of the power of the system, the time available to shoot the ejector mass, $\Delta t_{shooting}$ (Eq. (24)), and the ejection velocity, v_e, which is conservatively taken to be 200 m/s [32,36].

$$m_{launch} = \frac{2P_k\Delta t_{shooting}}{{v_e}^2} \tag{23}$$

$$\Delta t_{shooting} = \left(\frac{10^\circ}{360^\circ}\right)T_{rot} \tag{24}$$

Further, the mass ejector can only fire in a $\pm 5^\circ$ window of the desired thrust direction. As such, the asteroid material extracted can only be launched within a particular timeframe that is dependent on the period of rotation of the asteroid, T_{rot}. The mass ejector is limited to one launch per rotation, and the mass ejected is assumed to remain constant throughout the redirection timeframe. The mass ejector can, however, launch mass less frequently if the rotation rate is sufficiently large, with the upper bound of one projectile launch per minute. Lastly, delta-v can be determined through the summation of the finite delta-v for each projectile, shown in Eq. (25), over the duration of the redirection [32].

$$\delta v = \frac{m_{launch}}{m_{ast}(t)} v_e \tag{25}$$

4.6. Attributes determined from Monte Carlo analysis

The Monte Carlo analysis was used to determine delta-v, coefficient of variation, and mass-loss ratio for each redirection method. The results of Monte Carlo simulation for the average delta-v, standard deviation, standard error, and coefficient of variation for each redirection method are outlined in Table 9. As expected, the gravity tractor has the lowest delta-v capabilities and the lowest coefficient of variation. The ion beam and tugboat redirection methods have similar robustness, since they are minimally affected by variation in the asteroid composition and use the same thrusting mechanism. Contrastingly, the laser sublimation method is largely affected by asteroid variation; and as such, it is seen to have a low robustness. It should be noted that delta-v for the laser sublimation approach was considerably reduced, due to the effect of rotational period on its ability to induce sublimation. In some instances, there was insufficient time for sublimation to occur given the spot size and rotational speed. In more complex analyses, a laser spot that moves in the same direction as the asteroid's rotation might be able to ensure the system is always

Table 9
Delta-v and performance robustness parameters.

	ΔV_{ave} [km/s]	$\sigma_{\Delta V}$	Standard error	C_v
RM-01 Ion beam	0.0078	0.0093	9.32×10^{-5}	1.19
RM-02 Tugboat	0.0152	0.0181	1.81×10^{-4}	1.19
RM-03 Gravitational tractor	6.06×10^{-8}	4.57×10^{-8}	4.57×10^{-10}	0.75
RM-04 Laser sublimation	7.50×10^{-5}	2.18×10^{-4}	2.30×10^{-6}	2.90
RM-05 Mass ejector	0.0367	0.0594	5.94×10^{-4}	1.62

Table 10
Asteroid alteration values.

CR-3 Asteroid alteration	M_r (%)	σ_{Mr}	Standard error
RM-01 Ion beam shepherd	0	–	–
RM-02 Tugboat	0	–	–
RM-03 Gravitational tractor	0	–	–
RM-04 Laser sublimation	0.023	6.66×10^{-4}	6.66×10^{-6}
RM-05 Mass ejector	13.82	0.1812	0.0018

able to induce a sublimation thrust on the asteroid. However, in this case, when the method was unable to induce sublimation, the asteroid experienced no resulting change in velocity.

In Table 10, the mass-loss ratios, standard deviation and standard error are presented for each redirection method. The ion beam, tugboat, and gravity tractor methods have minimal effect on the asteroid mass during redirection, and hence have been assigned values of zero. In particular, the ion beam and gravitational tractor methods are hovering techniques that interact minimally with the asteroid surface. The ion beam method may cause small amounts of debris to be lifted from the surface; however, it is likely that the quantity would be negligible with respect to the asteroid's total mass and that much of the debris would resettle on the asteroid surface. The gravitational tractor method specifically attempts to avoid interaction with the asteroid by angling its thrusters away from the asteroid surface. It is possible that the thrust plume may be wider than anticipated, but again the overall effect is expected to be minimal. The tugboat method requires two contact spots, and while some debris may be lifted during the descent and attachment phases, it is expected to be an insignificant change in mass. The mass-loss ratio is more prominent in the laser sublimation and mass ejector methods, since these methods generate thrust through mass removal. The low percentage of mass alteration from the laser sublimation approach can likely be attributed to short rotation periods of the asteroid reducing the available sublimation time. The mass ejector has the highest mass-loss ratio, and while the average is at approximately 14%, the mass-loss ratio can increase significantly for small asteroids.

4.7. Attributes for TRRA and mission risk analysis

This section outlines the technical readiness levels and need values for the three primary technologies employed by each redirection method, as well as the three major mission risks associated with the method. Table 11 outlines the TRRA and mission risk values assigned to each redirection method and depicts the results of the integrated TRRA and mission risk on a fever chart. The references provided for each technology and risk provide some insight into the values assigned to each method.

4.8. Long-term value of redirection methods

The long-term value evaluates the system extensibility and reusability of each redirection method. To determine the extensibility and reusability of each redirection method limiting technologies are considered with respect to operational lifetime. For example, the ion thrusters used in the ion beam, tugboat, and gravitational tractor methods may have a continuous use lifetime of 5.5+ years [39]. This allows for assigning a high potential for system extensibility for both the ion beam and gravitational tractor methods, since they could be easily adapted for an asteroid flyby mission or something similar. Moreover, it is likely with moderate modification, including refueling, these spacecraft could be applied to a secondary mission. The tugboat method, however, has very low potential for a secondary mission, since it is unlikely the system attachment method to the asteroid would be capable of multiple missions. It does have the potential to be used for asteroid orbit maintenance and station-keeping after capture, thus attributing it some minor extensibility. The laser sublimation method has been shown to exhibit poor long-term performance, due to system degradation from sublimated mass [19]. Since this degradation has been shown to considerably affect the thrusting capabilities of the system by over two orders of magnitude in less than two years, it is likely that the system would be unable to perform another asteroid redirection mission. However, a flyby or similar extended mission design might be capable with minor system modifications. Similar to the tugboat approach, the mass ejector method is likely impractical for a secondary redirection mission, due to its lander system. It is further improbable that an extended mission would be feasible with the mass ejector system without major system modifications. Table 12 outlines the long-term value attributes assigned for each redirection method.

5. Assessment techniques

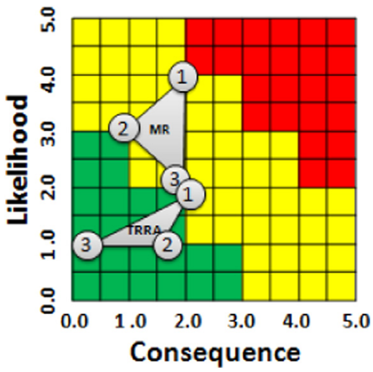
This section will utilize three distinct assessment techniques to examine the attributes for each redirection method. The three assessment techniques, i.e. Analytical Hierarchy Process (AHP), a utility-based approach, and a fuzzy aggregation mechanism, each has particular advantages that provide unique insight into the multi-criteria assessment process.

5.1. Analytical Hierarchy Process

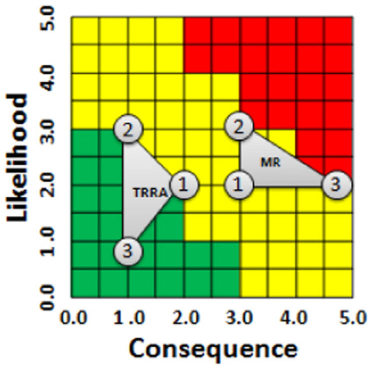
The analytical Hierarchy Process (AHP) is a well established assessment method in the literature, which utilizes relative pair-wise assessments. The AHP assigns relative preference values to each redirection method for a given criterion, and relative importance values to each criterion. The relative preference/importance values are found through pair-wise comparison tables. The relative importance values can be seen in Tables 22–24, and the relative preference comparisons can be seen in Tables 13–20, with overall preference values summarized in Table 21. It is important to note that the pairwise comparisons in each table undergo column normalization prior to determining the overall preference/importance. The column normalization for each table is achieved using the following

Table 11
TRRA and mission risk descriptions, values, and matrices.

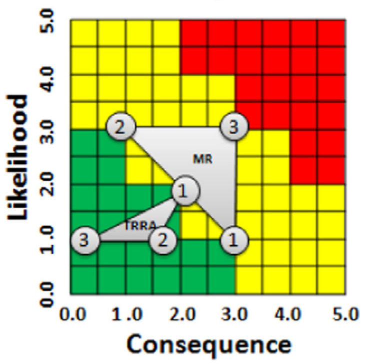
RM-01. Ion beam	***Technology description***	**R&D^3**	**TRL**	**TNV**
	T1. Ion thrusters [32]	2	4	4
	T2. Autonomous hovering GNC [32]	1	4	3
	T3. Propellant storage [37]	1	7	1
			$I_{TRRA}=$	**5.6**
	Mission Risk description [7]		L_{MR}	C_{MR}
	M1. Reduced ion beam force on asteroid due to elevated debris interfering with ion beam surface force		4	2
	M2. Reduced fuel directed towards thrusting due to uncertainty in the gravitational field and additional fuel required for stabilization and position-keeping		3	1
	M3. Inconsistent hover distance from asteroid due to uncertainty in the gravitational field effecting net thrust on the asteroid		2	2
			E_{MR} (%)=	**93.25%**



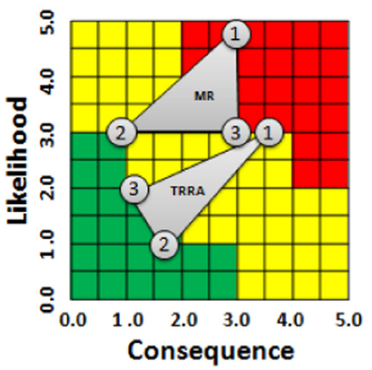
RM-02. Tugboat	***Technology description***	**R&D^3**	**TRL**	**TNV**
	T1. Ion thrusters [32]	2	4	4
	T2. Lander [32]	3	5	4
	T3. Gimbal system [38]	1	5	3
			$I_{TRRA}=$	**7.8**
	Mission risk description [7]		L_{MR}	C_{MR}
	M1. Asteroid geometry causes a decrease in the available time intervals for providing thrust in the proper direction through the center of gravity		2	3
	M2. Asteroid geometry causes a non-ideal landing orientation reducing thrust angle range		3	3
	M3. Asteroid composition uncertainty causes failure of lander attachment to asteroid surface		2	5
			E_{MR} (%) =	**65.00%**



RM-03. Gravity tractor	***Technology description***	**R&D^3**	**TRL**	**TNV**
	T1. Ion thrusters [32]	2	4	4
	T2. Autonomous hovering GNC [32]	1	4	3
	T3. Propellant storage [37]	1	7	1
			$I_{TRRA}=$	**5.6**
	Mission risk description [7]		L_{MR}	C_{MR}
	M1. Thruster angle insufficient to ensure exhaust plume does not impinge the surface of the asteroid		1	3
	M2. Reduced fuel directed towards thrusting due to uncertainty in the gravitational field and additional fuel required for stabilization and position-keeping		3	1
	M3. Inconsistent hover distance from asteroid due to uncertainty in the gravitational field effecting net thrust on the asteroid		3	3
			E_{MR} (%) =	**86.25%**



RM-04. Laser	***Technology description***	**R&D^3**	**TRL**	**TNV**
	T1. Laser [32]	3	3	5
	T2. Autonomous hovering GNC [32]	1	4	3
	T3. Thermal regulation [37]	2	3	1
			$I_{TRRA}=$	**14.8**
	Mission risk description [7]		L_{MR}	C_{MR}
	M1. Thrust degradation due to deposited re-condensed ejecta material		5	3
	M2. Reduced fuel directed towards thrusting due to uncertainty in the gravitational field and additional fuel required for stabilization and position-keeping		3	1
	M3. Inconsistent hover distance from asteroid due to uncertainty in the gravitational field effecting net thrust on the asteroid		3	3
			E_{MR} (%)=	**37.25%**



RM-05. Mass ejector	***Technology description***	**R&D^3**	**TRL**	**TNV**
	T1. Lander [32]	3	5	4
	T2. Drill/Coring mechanism [32]	2	3	4

Table 11 (*continued*)

T3. Rail gun [32]	2	5		4
		I_{TRRA}=		**11**
Mission risk description [7]			L_{MR}	C_{MR}
M1. Asteroid geometry causes a decrease in the available time intervals for providing thrust in the proper direction through the center of gravity			2	3
M2. Drill unable to mine sufficient mass to eject			3	4
M3. Dust deposits collecting on lander disabling operation			3	5
			E_{MR} (%)=	**45.00%**

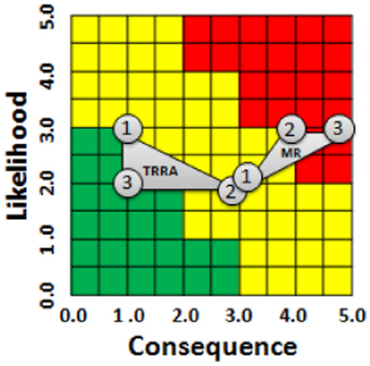


Table 12
Long-term value table [7].

Long-term value	RM-01	RM-02	RM-03	RM-04	RM-05
System extensibility	5	2	5	4	1
Reusability	3	1	3	1	1
Average	**4**	**1.5**	**4**	**2.5**	**1**

Table 13
Relative preference for delta-v.

CR-1	RM-01	RM-02	RM-03	RM-04	RM-05
RM-01	1	1/2	125000	125	1/4
RM-02	2	1	250000	250	1/2
RM-03	1/125000	1/250000	1	1/1000	1/500000
RM-04	1/125	1/250	1000	1	1/500
RM-05	4	2	500000	500	1

Table 14
Relative preference for performance robustness.

CR-2	RM-01	RM-02	RM-03	RM-04	RM-05
RM-01	1	1	1/2	4	2
RM-02	1	1	1/2	4	2
RM-03	2	2	1	8	4
RM-04	1/4	1/4	1/8	1	1/2
RM-05	1/2	1/2	1/4	2	1

Table 15
Relative preference for asteroid alteration.

CR-3	RM-01	RM-02	RM-03	RM-04	RM-05
RM-01	1	1	1	2	8
RM-02	1	1	1	2	8
RM-03	1	1	1	2	8
RM-04	1/2	1/2	1/2	1	4
RM-05	1/8	1/8	1/8	1/4	1

Table 16
Relative preference for system cost.

CR-4	RM-01	RM-02	RM-03	RM-04	RM-05
RM-01	1	2	2/3	3	4
RM-02	1/2	1	1/2	2	3
RM-03	3/2	2	1	3	4
RM-04	1/3	1/2	1/3	1	2
RM-05	1/4	1/3	1/4	1/2	1

Table 17
Relative preference for ave. required power.

CR-5	RM-01	RM-02	RM-03	RM-04	RM-05
RM-01	1	1	1	2	4
RM-02	1	1	1	2	4
RM-03	1	1	1	2	4
RM-04	1/2	1/2	1/2	1	2
RM-05	1/4	1/4	1/4	1/2	1

Table 18
Relative preference for TRRA.

CR-6	RM-01	RM-02	RM-03	RM-04	RM-05
RM-01	1	2	1	4	6
RM-02	1/2	1	1/2	2	3
RM-03	1	2	1	4	6
RM-04	1/4	1/2	1/4	1	2
RM-05	1/6	1/3	1/6	1/2	1

Table 19
Relative preference for mission risk.

CR-7	RM-01	RM-02	RM-03	RM-04	RM-05
RM-01	1	3	2	8	4
RM-02	1/3	1	1/2	4	2
RM-03	1/2	2	1	6	3
RM-04	1/8	1/4	1/6	1	1/2
RM-05	1/4	1/2	1/3	2	1

formula,

$$\tilde{n}_{ij} = \frac{\tilde{r}_{ij}}{\sum_{i=1}^{N} \tilde{r}_{ij}} \tag{26}$$

where $\tilde{r}$ is the particular relative importance value at the column index i and the row index j, n is the normalized value at that index, and N is the total number of values in the column. The overall relative preference/importance is then determined using Eq. (27) by taking the mean value of the row after column normalization,

$$\tilde{w}_i = \frac{1}{N}\sum_{j=1}^{N} \tilde{n}_{ij} \tag{27}$$

where $\tilde{w}$ represents the overall weight, and N represents the total number of values in the row. These overall relative preference and importance values are then aggregated to quantify the overall score of the method. It is important to note that the typical range used to describe the preference is from 1 to 9. However, in the relative preference table for delta-v a much larger scale was required to describe the six order of magnitude range between the delta-v attributes assigned to each method. As such, a more representative scale that ranged from 1 to 500,000 was employed.

As in a previous study [7], three relative importance tables are utilized, i.e., cost-based (risk seeking), balanced, and performance-based (risk averse). However, this assessment provides a new set of pair-wise comparisons and modified overall importance values due to the incorporation of different criteria. The three different importance tables are introduced to provide a more robust comparison of investor interests. The cost-based pair-wise comparison table, Table 23, emphasizes the importance of delta-v, system cost, and asteroid alteration, with lower emphasis on TRRA, mission risk, and performance robustness. Conversely, the performance-based table, Table 24, weighs the TRRA, mission risk, and performance robustness criteria most heavily, with reduced importance assigned to delta-v, system cost, and asteroid alteration. The balanced assessment, Table 22, represents a neutral ground between the extremes presented in the cost-based and performance-based importance weightings.

It is important to acknowledge that a consistency analysis was performed for each preference and importance table [40]. The consistency analysis is based on the following logic for any three entries A, B and C of a table: if (A | B=x) and (B | C=y then (A | C=$x \times y$).

Table 20
Relative preference for long-term value.

CR-8	RM-01	RM-02	RM-03	RM-04	RM-05
RM-01	1	3	1	5	8
RM-02	1/3	1	1/3	1/2	2
RM-03	1	3	1	5	8
RM-04	1/5	2	1/5	1	4
RM-05	1/8	1/2	1/8	1/4	1

Table 21
Overall (normalized) relative preferences for each criterion.

ID	CR-01	CR-02	CR-03	CR-04	CR-05	CR-06	CR-07	CR-08
RM-01	0.1427	0.2105	0.2759	0.2932	0.2667	0.3419	0.4318	0.3683
RM-02	0.2854	0.2105	0.2759	0.1835	0.2667	0.1710	0.1610	0.0971
RM-03	0.0000	0.4211	0.2759	0.3453	0.2667	0.3419	0.2688	0.3683
RM-04	0.0011	0.0526	0.1379	0.1096	0.1333	0.0910	0.0461	0.1240
RM-05	0.5708	0.1053	0.0345	0.0684	0.0667	0.0541	0.0922	0.0423

Table 22
Criteria relative importance for the balanced approach.

ID	Criteria	CR-1	CR-2	CR-3	CR-4	CR-5	CR-6	CR-7	CR-8	$\tilde{w}$
CR-1	Delta-v	1	2	2	1/2	6	4	3	5	**0.2222**
CR-2	Robustness	1/2	1	2	1/3	5	1	1/2	4	**0.1134**
CR-3	Asteroid alteration	1/2	1/2	1	1/3	5	1	1/2	4	**0.0962**
CR-4	System cost	2	3	3	1	7	3	2	6	**0.2722**
CR-5	Power	1/6	1/5	1/5	1/7	1	1/4	1/5	1/2	**0.0258**
CR-6	TRRA	1/4	1	1	1/3	4	1	1/2	3	**0.0881**
CR-7	Mission risk	1/3	2	2	1/2	5	2	1	4	**0.1459**
CR-8	Long-term value	1/5	1/4	1/4	1/6	2	1/3	1/4	1	**0.0361**

Table 23
Criteria relative importance for cost-based approach.

ID	Criteria	CR-1	CR-2	CR-3	CR-4	CR-5	CR-6	CR-7	CR-8	$\tilde{w}$
CR-1	Delta-v	1	4	2	1/2	8	6	5	7	**0.2598**
CR-2	Robustness	1/4	1	1/2	1/5	3	1	1/2	2	**0.0631**
CR-3	Asteroid alteration	1/2	2	1	1/3	7	3	2	6	**0.1513**
CR-4	System cost	2	5	3	1	9	5	4	8	**0.3282**
CR-5	Power	1/8	1/3	1/7	1/9	1	1/2	1/3	1/2	**0.0257**
CR-6	TRRA	1/6	1	1/3	1/5	2	1	1/2	1	**0.0499**
CR-7	Mission risk	1/5	2	1/2	1/4	3	2	1	2	**0.0828**
CR-8	Long-term value	1/7	1/2	1/6	1/8	2	1	1/2	1	**0.0391**

Table 24
Criteria relative importance for performance-based approach.

ID	Criteria	CR-1	CR-2	CR-3	CR-4	CR-5	CR-6	CR-7	CR-8	$\tilde{w}$
CR-1	Delta-v	1	1/2	2	1/2	4	2	1	3	**0.1419**
CR-2	Robustness	2	1	4	1	7	1	1/2	6	**0.1854**
CR-3	Asteroid alteration	1/2	1/4	1	1/3	3	1/3	1/4	2	**0.0600**
CR-4	System cost	2	1	3	1	5	1	1/2	4	**0.1622**
CR-5	Power	1/4	1/7	1/3	1/5	1	1/6	1/7	1/2	**0.0263**
CR-6	TRRA	1/2	1	3	1	6	1	1/2	5	**0.1456**
CR-7	Mission risk	1	2	4	2	7	2	1	6	**0.2411**
CR-8	Long-term value	1/3	1/6	1/2	1/4	2	1/5	1/6	1	**0.0375**

Table 25
Consistency ratios for preference and importance tables.

Table	13	14	15	16	17	18	19	20	22	23	24
C_R **(%)**	0	0	0	1.25	0	0.22	0.81	4.33	3.33	2.04	3.18

Consequently, an ideally consistent table would exhibit the above-mentioned logic for all its entries as closely as possible. To ensure the consistency of each reciprocal table, the consistency index, C_I, is obtained using Eq. (28) [40].

$$C_I = \frac{\lambda_{max} - n}{n-1} \tag{28}$$

where λ_{max} is the largest eigenvalue of the table, and n is the number of rows/columns in the table. It can be shown that for an ideally consistent table, the largest eigenvalue is equal to n, and hence the consistency index is equal to zero [40]. On the other hand, a random consistency index R_I can be defined, as a representative of a clearly inconsistent (and poorly constructed) table of a given dimension, by taking the average consistency index for a large number of randomly generated tables of the given dimension. In particular, the random consistency indices for 5×5 and 8×8 tables, which are used in this analysis, are computed as 1.12 and 1.41, respectively [41]. To measure the proximity of the logical state of a table to being ideally consistent, a consistency ratio, C_R, can then be defined by Eq. (29) [40].

$$C_R = \frac{C_I}{R_I} \tag{29}$$

It has further been shown that a reciprocal table with a consistency ratio below 10% is acceptably consistent [40]. A consistency analysis has been performed for each preference and importance table, and the consistency ratios are shown in Table 25, all of which are well below 10%.

5.2. Utility-based approach

The utility-based approach assigns a utility value to each criterion through the use of utility functions. Utility values ranging from 0 to 1 are assigned to each attribute according to the utility function for its criterion. The utility-based method calculates the total utility for each redirection method using the following relation in Eq. (30).

$$U_{RM} = u_1(c_1) \cdot \tilde{w}_1 + \ldots + u_n(c_n) \cdot \tilde{w}_n \tag{30}$$

where U is the total utility for each redirection method, $u(c)$ is the utility function for the indexed criteria evaluated at the assigned criteria value, c, and $\tilde{w}$ is the normalized weight assigned to that particular criterion. The three criteria weightings discussed for the AHP method will be utilized here as the normalized weights. The utility functions, shown in Fig. 3, primarily follow "*direct-S*" and "*reverse-S*" trends, and are defined according to a previous work [12]. The objective of asteroid resource exploitation can be seen in the utility functions. The definition of each criterion's utility function correlates an increased utility value with an increased opportunity for profitability. This relationship can be seen most clearly in the system cost-criterion, which highlights a much larger preference to low-cost systems. Similarly, the performance robustness and asteroid alteration criteria follow *reverse-S* trends, since low performance of an attribute with respect to these criteria indicates lower target availability and lower returned mass. The delta-v utility function rewards redirection methods with higher capability, since this indicates they are able to redirect more asteroid material and increases the range of available target asteroids. The mission risk and long-term value utility functions follow *direct-S* trends that indicate a greater value to low-risk missions and the ability to reuse or re-purpose the redirection method. The irregularity of the *reverse-S* trend visible in the power utility function is due to the greater availability of lower power systems, which makes lower power methods considerably preferable. Lastly, the integrated TRRA utility function has a trend that follows the low-medium-high risk levels of a typical fever chart, where the maximum integrated TRRA value is equal to the sum of three technologies each with the maximum Δ-TRL, TNV and R&D^3.

5.3. Fuzzy aggregation mechanism

The fuzzy aggregation mechanism was first proposed in [42]. This method utilizes T-norms, T-conorms, satisfaction memberships, and *wish* attributes to assess the overall satisfaction of a particular redirection method to the design criteria. In fuzzy aggregation, the wish attributes are assigned to each criterion by means of a satisfaction membership function. The satisfaction membership functions used in this aggregation are opted the same as the utility functions presented in Section 5.2. The overall satisfaction of each redirection method can then be

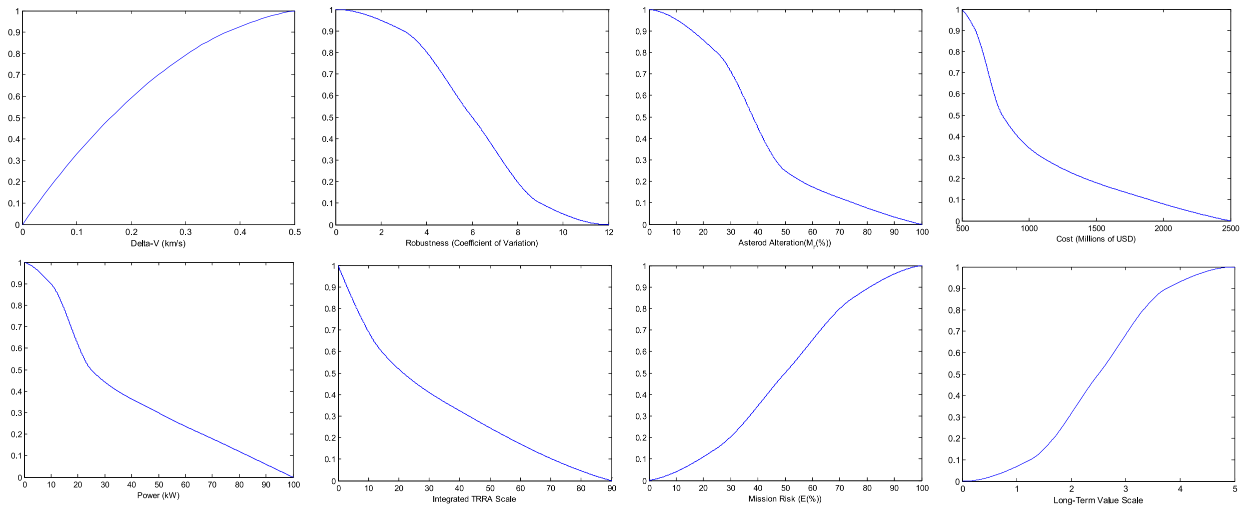


Fig. 3. Utility functions for the assessment criteria.

Table 26
Summary of attributes.

ID	Criteria	RM-01	RM-02	RM-03	RM-04	RM-05
CR-1	Delta-v (km/s)	0.0078	0.015	6.1×10^{-8}	7.5×10^{-5}	0.037
CR-2	Performance robustness	1.19	1.19	0.75	2.90	1.62
CR-3	Asteroid alteration (%)	0	0	0	0.023	13.82
CR-4	System cost (USD)	602M	871M	545M	1.55B	2.39B
CR-5	Power (kW)	10	10	10	16	20
CR-6	Technology readiness and risk	5.6	7.8	5.6	14.8	22
CR-7	Mission risk (%)	93.25	65.00	86.25	37.25	45.00
CR-8	Long-term value	4	1.5	4	2.5	1

defined using Eq. (31) [24],

$$\mu_w^{(q)} \equiv T^{(q)}(w_1, \ldots, w_n); q > 0 \tag{31}$$

where $\mu_w^{(q)}$ is the q-parameterized overall satisfaction value, w_i are wish attributes, and $T^{(q)}$ is the q-parameterized T-norm operator, defined by Eq. (32),

$$T^{(q)}(w_1, \ldots, w_n) \equiv 1 - S^{(q)}((1-w_1), \ldots, (1-w_n)) \tag{32}$$

where $S^{(q)}$ is the T-conorm operator defined by Eq. (33).

$$S^{(q)}(b_1, \ldots, b_n) \equiv \left[b_1^q + (1-b_1^q)\left[\ldots\left[b_{n-2}^q + (1-b_{n-2}^q)\left[b_{n-1}^q + (1-b_{n-1}^q)b_n^q\right]\right]\ldots\right]\right]^{1/q} \tag{33}$$

The q value represents the attitude of the assessor with respect to the method's overall satisfaction of the wish attributes. The effects of the q parameter can be more easily understood through the investigation of extreme cases, i.e., when q approaches zero and infinity. Eqs. (34) and (35) show that as the q parameter approaches zero, the T-norm approaches the product of the attributes, whereas when q approaches infinity the T-norm approaches the minimum value of the attributes [43].

$$q \to \infty : T^{(q)}(w_1, \ldots, w_n) = T_{min}(w_1, \ldots, w_n) \tag{34}$$

$$q \to 0 : T^{(q)}(w_1, \ldots, w_n) = T_{\times}(w_1, \ldots, w_n) \tag{35}$$

As such, a larger q value implies a more conservative approach, whereas a q value closer to zero can be considered as more aggressive.

6. Assessment results and discussions

Table 26 lists a summary of attributes for each redirection method. A brief discussion of the results from each assessment will be discussed in this section, followed by a general overall evaluation of the results.

6.1. Analytical Hierarchy Process

Table 27 outlines the performance of each redirection method using AHP, with a bar graph of the values in Fig. 4. The three different importance weightings, i.e., cost-based (risk-seeking), balanced, and performance-based (risk-averse), are presented for each method. It is immediately clear from the results that the three weightings have highlighted the nature of the risk associated with each method. The results indicate that the tugboat, laser sublimation, and mass ejector methods are of higher risk but offer the potential for greater return, whereas the ion beam and gravity tractor methods provide lower risk alternatives. However, the ion beam and gravity tractor methods have the overall strongest performance, well out-performing the other free-flying approach, i.e., laser sublimation. The tugboat performed fairly well, and while it is comparable with the other landed redirection method, the mass ejector, it is more consistent and outperforms the mass ejector across all three weightings. It is interesting to note that the mass ejector method considerably benefits with the risk-seeking weighting, which suggests that it has high performance capability but high risk, thus presenting great opportunity for profit.

6.2. Utility-based approach

The utility values assigned to each attribute are presented in Table 28 for each redirection method. The results of the weighted utility-based approach are outlined in Table 29 and Fig. 5. As in the AHP analysis the ion beam, gravity tractor, and tugboat methods perform well. However, unlike in the AHP assessment, the ion beam method did not outperform the gravity tractor in all three weightings. For the performance-based weighting the gravity tractor has the highest score of all the methods, but it is surpassed by the ion beam method for the balanced and cost-based criteria weightings. The tugboat method has a slightly lower overall performance than the ion beam and gravity tractor methods; making it a much more competitive approach than in the AHP analysis. The laser sublimation approach still maintains the lowest scores across all three weightings, with the mass ejector method garnering slightly better results.

Table 27
AHP aggregation results.

ID	Method	Performance-based	Balanced	Cost-based
RM-01	Ion beam	0.2981	0.2753	0.2624
RM-02	Tugboat	0.2002	0.2127	0.2219
RM-03	Gravitational tractor	0.2860	0.2579	0.2422
RM-04	Laser sublimation	0.0685	0.0720	0.0771
RM-05	Mass ejector	0.1471	0.1821	0.1963

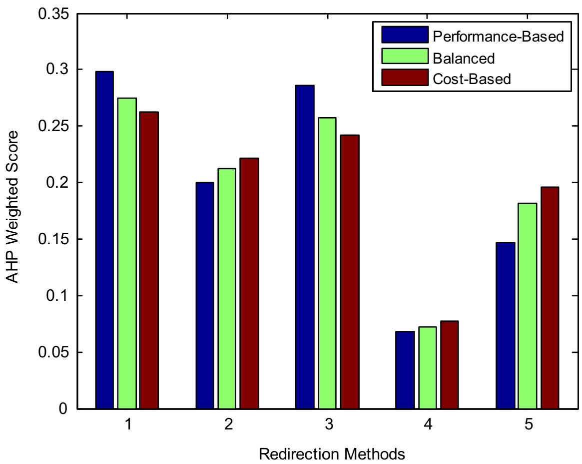


Fig. 4. AHP redirection method scores.

Table 29
Utility-based aggregation results.

ID	Method	Performance-based	Balanced	Cost-based
RM-01	Ion beam shepherd	0.7571	0.7058	0.6885
RM-02	Tugboat	0.6534	0.6250	0.6202
RM-03	Gravitational tractor	0.7710	0.7000	0.6708
RM-04	Laser sublimation	0.3328	0.3551	0.3953
RM-05	Mass ejector	0.4611	0.4751	0.4981

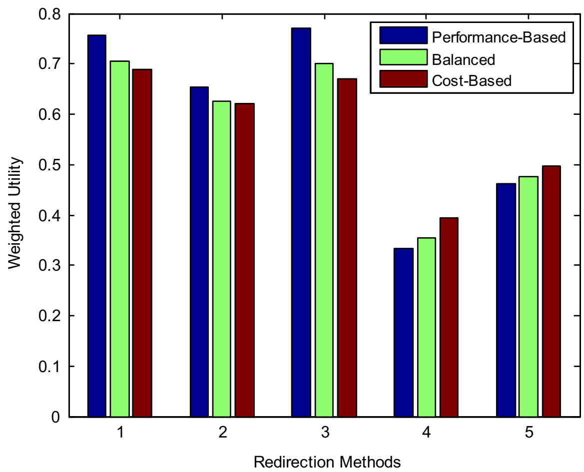


Fig. 5. Utility method redirection method scores.

Table 28
Utility function values.

ID	Criteria	RM-01	RM-02	RM-03	RM-04	RM-05
CR-1	Delta-v	0.1360	0.2530	1.098×10^{-6}	0.0013	0.5568
CR-2	Performance robustness	0.6894	0.6894	0.9000	0.0024	0.4308
CR-3	Asteroid alteration	1.0000	1.0000	1.0000	1.0000	0.9215
CR-4	System cost	0.8445	0.7093	0.8679	0.4570	0.3302
CR-5	Power	0.9000	0.9000	0.9000	0.7473	0.6167
CR-6	Technology readiness and risk	0.8166	0.7510	0.8166	0.5937	0.4946
CR-7	Mission risk	0.9771	0.7302	0.9368	0.3037	0.4255
CR-8	Long-term value	0.9309	0.1493	0.9309	0.5000	0.0691

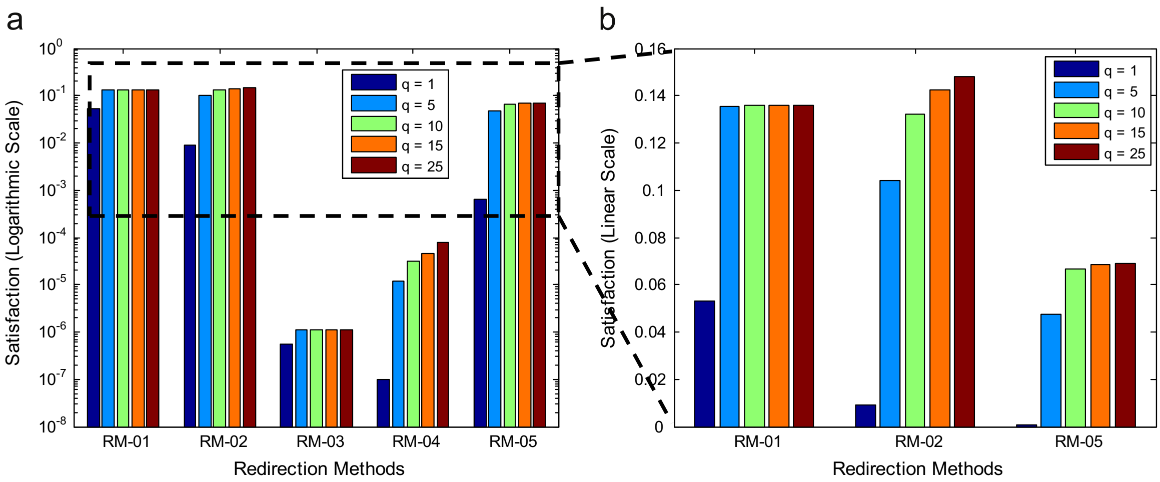


Fig. 6. (a) Fuzzy aggregation overall satisfaction values. (b) Fuzzy aggregation overall satisfaction values (top 3).

6.3. Fuzzy aggregation

The fuzzy aggregation mechanism provides a very stark contrast to the Analytical Hierarchy Process and the utility-based approaches. A single attribute does not greatly affect the overall results of the AHP and utility-based approaches, since their aggregation is additive with respect to the criteria. Contrastingly, the fuzzy aggregation approach is highly sensitive to the individual attributes assigned to each criterion, due to the multiplicative nature of the aggregation. As such, a method with a very low satisfaction value for a particular attribute will suffer much more significantly for the fuzzy aggregation approach than with AHP or utility-based. This is highlighted in the results for fuzzy aggregation presented in Figs. 6a and b. As in the previous two aggregations, the ion beam method performs well. However, the gravity tractor approach has very low overall satisfaction compared to the previous assessments. This low satisfaction can be ascribed to the very low satisfaction of the delta-v attribute. Since the fuzzy aggregation is multiplicative, the effect of this extremely low satisfaction is more severe on the overall performance of the method. It is interesting to note that the tugboat method benefits from this change in assessment, and in fact has the highest overall satisfaction of all the methods for higher q values. The mass ejector also maintains fairly high performance and performs better than in the previous assessments. The laser sublimation approach has a low satisfaction, but surprisingly outperforms the gravity tractor method. The low satisfaction of delta-v for the laser sublimation method makes it considerably less satisfactory than the ion beam, tugboat, and mass ejector methods. However, the satisfaction value of delta-v for the laser sublimation method is still considerably greater than that of the gravity tractor. Lastly, the variation of the q parameter indicates that there is lower discrepancy between the ion beam's product satisfaction and minimum satisfaction value. Whereas the high variability of the satisfaction values for the tugboat method indicate a greater range between the minimum and product satisfaction values. The overall satisfactions of the ion beam and gravity tractor methods are too similar to assign a preference between the two methods with respect to the fuzzy aggregation mechanism.

6.4. General discussions

Through investigating the attributes with three different assessment schemes, a more sensitive and robust analysis has been completed. In particular, the analysis provides insight into the strengths and weaknesses of each redirection method, which will be discussed in this section.

The mass ejector method is fairly consistent across all three aggregations. While it is not the best performing method in any of the assessments, it is also not the lowest performing. It is particularly noteworthy that unlike the gravity tractor and laser sublimation methods, which suffer greatly in the multiplicative fuzzy aggregation approach, the mass ejector method remains fairly competitive. This can be ascribed to the lack of any particular attribute that exhibits an extremely low preference, utility or satisfaction value. In addition, the mass ejector has the best performance with respect to the delta-v criterion. As a result, although it generally has lower attribute values with respect to the other redirection methods, it still scores reasonably well in each aggregation. It should be noted that if the asteroid diameter range was reduced, the delta-v capability of the method could be considerably increased but at the expense of mass-loss ratio. The very large delta-v capability of the mass ejector method makes it very enticing for risk-seeking investors given the high return potential.

The laser sublimation method has the weakest performance across all three assessment approaches. This is a clear indication that a singular laser sublimation spacecraft, as currently modeled, is not suitable for the scope of this redirection mission. The low performance is mostly accredited to the high cost and high risk of the method, as well as its low average delta-v. These attributes can be considerably improved through the use of multiple laser sublimation spacecraft. In addition to increasing the available induced power on the asteroid surface for sublimation, a multiple spacecraft approach reduces mission risk and can potentially reduce the system cost. Moreover, the laser sublimation approach might be more viable for a target range of smaller asteroid diameters, since the mass ejected relative to the total asteroid mass will be greater. Further, targeting only asteroids with slow rotation rates can significantly improve the performance of the redirection capabilities of the laser sublimation method. The amount of mass ejected can also be increased by narrowing the target range of asteroids to those with the most viable chemical compositions with respect to sublimation. Although the laser sublimation approach might be applicable to a narrower band of asteroids, the low robustness of this method affects its overall performance with respect to the scope of this mission.

The performance of the gravity tractor approach varies quite notably across the three assessment approaches. It is the highest performing method with respect to the Analytical Hierarchy Process and utility-based approaches, whereas it has one of the lowest overall satisfactions for the fuzzy aggregation. As discussed previously, this stark contrast can be attributed to the difference between the assessment approaches, i.e., additive versus multiplicative. The delta-v parameter for the gravity tractor is extremely low compared to that of the other redirection methods, and as such has very low satisfaction in the multiplicative aggregation. However, in the additive assessment approaches, i.e., AHP and utility-based, the effect of the single low attribute is negligible since all the other attributes for the gravity tractor have high preference and utility. The gravity tractor outperforms all of the other redirection methods with respect to the performance robustness, asteroid alteration, system cost, power, TRRA, and long-term value criteria. It has a high value, though not the highest, for mission risk, and only performs poorly with respect to the delta-v criterion. In consideration of these results, it is clear that the delta-v capability of the gravity tractor method is the greatest deterrent to its implementation. In particular, the gravity tractor method might have considerably better performance if the mission constraints on the timeframe for redirection were increased or if the target range of asteroid diameters was reduced. This method could also potentially benefit from increased mass even though this would affect the launch costs of the mission. Some studies consider the capture of a small asteroid or boulder to increase the mass of the asteroid [44]; however, the added complexity of such a procedure would need to be investigated. The gravity tractor method might still be valuable for this particular mission depending on the amount of material an investor hopes to be able to ascertain. An investigation into the available asteroid mass and the composition of such targets, within the delta-v capabilities of the gravity tractor, would be a valuable step to determine the overall viability of the gravity tractor method.

The tugboat and ion beam methods exhibit the best performance overall for landed and free-flying redirection methods, respectively. In particular the ion beam method shows particular promise with generally the highest scores across all three assessment approaches. The ion beam and tugboat methods both have a fairly balanced set of attributes, with no exceptionally low values. The ion beam method's greatest advantage over the tugboat approach, however, is the reduced complexity and risk associated with a free-flying approach. In contrast, the tugboat method benefits greatly from the ability to use all its propellant for redirection purposes. The ion beam method requires half of its fuel for station-keeping, which reduces its delta-v capabilities to approximately half that of the tugboat method. While both methods have their strengths and drawbacks, generally the ion beam method outperforms the tugboat method.

Lastly, the three aggregations also provide some insight into the preference of each redirection method with respect to risk. It can be seen that in the AHP analysis the tugboat, laser sublimation, and mass ejector methods perform better in the risk-seeking (cost-based) criteria weightings than in the risk-averse (performance-based) criteria weightings. This implies that these methods typically are of higher risk but with higher return. In the utility-based assessment, however, the tugboat method changes from performing better in the risk-seeking criteria weightings to higher scores in the risk-averse criteria weightings. This difference in performance in the two assessments might indicate that the tugboat is a more balanced approach with respect to risk and return on investment than the other two “risk-seeking” methods. The risk-averse preference of the ion beam and gravity tractor methods might also indicate that these methods are better candidates for a research or exploration mission.

7. Conclusions

The paper outlined the applicability of various deflection approaches to the redirection of a near-earth asteroid and discussed the major considerations with respect the implementation of such methods to a redirection mission. The five redirection methods considered, i.e., ion beam, tugboat, gravity tractor, laser sublimation, and mass ejector, were each defined in detail and assigned attributes according to the assessment criteria. The Monte Carlo simulation provided a robust analysis of the expected performance for each redirection method with respect to the target range of asteroids. The methods were compared through three assessment approaches, namely, Analytical Hierarchy Process, utility-based, and fuzzy aggregation. The three assessment approaches helped to identify bias in the assessments and key considerations with respect to each method, particularly with respect to delta-v capabilities. Overall, the ion beam and tugboat methods proved to be the most viable methods given the mission constraints, and further investigation into these methods would be advisable. In particular, considering the benefits of formation design for these two approaches may considerably lower their system cost, mission risk, and increase their delta-v capabilities in a shorter timeframe. The gravity tractor, laser sublimation, and mass ejector methods also show potentials for redirection missions, though narrowing the target asteroid population for each method would increase their viability. Furthermore, increasing the timeframe for redirection could be an asset for the gravity tractor and laser sublimation methods.

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