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A Systematic Assessment of Asteroid Redirection Methods for Resource Exploitation

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This paper provides a systematic comparison of the primary asteroid redirection techniques from the perspective of resource exploitation. The goal is to examine the methods for the redirection of a near-Earth asteroid to a stable and easily accessible orbit in the Earth-moon system in order to exploit asteroid resources. The context of resource exploitation provides clear constraints on the asteroid redirection mission, and a systematic comparison can be established within this scope. The paper describes each redirection method, and considers the major criteria for mission design. Moreover, a Monte Carlo analysis is performed to assess some attributes concerning the uncertainty intrinsic to asteroid redirection missions. The attributes for each redirection method are then aggregated using a multi-criteria decision making approach. Lastly, the results of the aggregation are presented and discussed.

Nomenclature

a_{gtug}	=	acceleration due to gravity tractor
C	=	risk consequence value
C_v	=	coefficient of variation
c_i	=	specific heat
d	=	asteroid-spacecraft distance
d_{ast}	=	asteroid diameter
E	=	expected percentage of objectives achieved
E_{sub}	=	enthalpy of sublimation
F_i	=	force (refer to subscript for further detail)
G	=	gravitational constant
g	=	gravity at sea-level
H	=	absolute magnitude
I_{sp}	=	specific impulse
k_a	=	thermal conductivity
L	=	risk likelihood value
M_r	=	mass-loss ratio
m_{ast}	=	asteroid mass
m_i	=	mass (refer to subscript for further detail)
Δm	=	change in mass

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$\dot{m}$	=	mass flow rate
P_I	=	absorbed power
P_T	=	estimated likelihood of not meeting performance requirements
Q_{rad}	=	heat loss due to radiation
Q_{cond}	=	heat loss due to conduction
R_i	=	specific risk event
r	=	asteroid radius
T_{ast}	=	asteroid period of rotation
T_{sub}	=	temperature of sublimation
T_0	=	initial temperature
t_i	=	time (refer to subscript for further detail)
Δt	=	timeframe for redirection
v_e	=	ejection velocity
v_{rot}	=	rotational velocity of the asteroid
$\bar{v}$	=	average velocity of ejecta plume
ΔV	=	delta-v
δv	=	finite delta-v
y	=	distance
α	=	inverse specific power
λ	=	scatter factor
$\mu_{\Delta V}$	=	average delta-v
η	=	thruster efficiency
ρ_{ast}	=	asteroid density
φ	=	half the angle of the exhaust cone
$\sigma_{\Delta V}$	=	standard deviation of delta-v

I. Introduction

ASTEROID resource exploitation has recently been a hot topic in the media[1], and has attracted the interest of both the private[2]and public space sectors[3]. The NASA challenge to engage in human exploration of an asteroid by 2025 has brought asteroid exploration to the forefront of the space industry[4]. With the increase in asteroid-focused programs from the public and private sectors, more than ever, research into a framework to redirect asteroids for resource utilization is relevant and pertinent.

Current research in asteroid manipulation mostly focuses on the deflection of potentially hazardous objects, often over long time periods. A wide variety of techniques are presented in the literature for asteroid deflection from nuclear impact methods to solar sail gravity tractors. While the effectiveness of these methods has been considered for deflection missions, rarely in the literature does one find asteroid manipulation methods applied to the case of resource exploitation or near-Earth asteroid (NEA) capture. This provides a unique opportunity to compare and contrast relevant methods developed for deflection to assess their viability for an NEA redirection mission. Through the use of a multi-criteria decision making method, this work shows the advantages and shortcomings of five different redirection methods with respect to a list of criteria relevant to resource exploitation. A systematic assessment of asteroid redirection methods provides useful insight into the viability of these techniques for asteroid redirection and resource exploitation.

II. Framework

This work follows a systematic approach to define the asteroid redirection problem from a resource exploitation perspective. The framework is divided into four main sections: problem formulation, assessment criteria, redirection methods, and the aggregation technique. The problem formulation section will define the scope and constraints of the problem, which are consistent with the requirements implicit to a viable resource exploitation mission. Relevant criteria and metrics will then be defined, and general approaches to their assessment will be explained. A list of redirection methods discussed in the literature, which are within the defined scope, will then be briefly presented. Lastly, the aggregation method will be described with the outcome of the aggregation presented in the results section of this paper.

A. Problem Formulation

The goal of this study is to determine the most viable techniques for the redirection of a near-Earth asteroid to a stable and easily accessible orbit in order to exploit its resources. For the purpose of this analysis, a simple circular capture orbit will be assumed, and all methods will first be assessed with regard to its simplest practical spacecraft configuration; usually a single or double spacecraft model. The advantages of multiple spacecraft and formation approaches will be considered separately in future studies.

The investigated near-Earth asteroids will range between 20m to 150m in diameter. The lower bound on asteroid diameter is defined by the smallest asteroids considered valuable for resource exploitation. As a result, envelopment methods that are frequently considered for diameters less than 20m are not well suited to this target range.[3,5]The upper bound of 150m provides a target range of NEAs that are not considered potentially hazardous objects (PHOs).[6] A PHO is defined to have an approximate diameter greater than 150m. Therefore, the above-mentioned range avoids the political complications of targeting larger asteroids for exploitation. In addition, since economic return is a key consideration, only carbonaceous (C-type) and metallic (M-type) asteroids will be targeted with capture delta-v's lower than the moon's escape velocity, 2.37km/s.[7] This work does not consider rubble-pile or highly porous asteroids, and assumes a monolithic spherical asteroid structure during assessment of redirection methods. Moreover, 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 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.

In order to ensure a systematic assessment of redirection techniques, the following list of constraints will be applied to the redirection methods for further specifying the scope. Table 1 outlines the constraints on the redirection methods in more detail.

Table 1. Redirection method constraints

Parameter	Definition	Validation
System Mass	The system must have a mass less than 6800 kg.	Atlas V maximum launch payload of 6860kg[8]
System Volume	The system must have a diameter of less than 4.572m and a length of less than 12.192m.	Atlas V max static payload envelope (specific details found in the Atlas V Launch Services User's Guide p.6-4)[8]
TRL	Each redirection method must be of TRL 2* or greater.	NASA TRL definitions document[9]
Timeframe	Timeframe for redirection from *rendez-vous* to asteroid capture must be less than 4 years.	Limited by reasonable project length for economic feasibility[10]

*TRL 2: Technology concept and/or application formulated[9]

B. Assessment Criteria

Asteroid redirection for a resource exploitation mission has a unique set of criteria and metrics. Table 2 outlines the criteria used for assessment of each redirection method. It is important to note that to ensure a robust assessment standard mission parameters, such as mass, volume and TRL, are included in this analysis alongside mission specific criteria, including asteroid alteration and delta-v.

Table 2. Assessment criteria

ID	Criteria	Description	Metric
CR-01	System mass	The total mass of the system required for the redirection method including any necessary propellants and equipment; where less mass is preferred.	Kg
CR-02	System volume	The total volume of the system required for the redirection method including any necessary propellants and equipment; where less volume is preferred.	m^3
CR-03	Technology readiness level (TRL)	The level of development or readiness of a technology; where a higher TRL is preferred.	TRL
CR-04	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-05	Mission risk	Any risk that may jeopardize the implementation or success of the mission; where less mission risk is preferred.	Risk Assessment Table
CR-06	System cost	The system cost for the redirection method, from development to completion; where lower system cost is preferred.	USD
CR-07	Average required power	The average electrical power required for operation of the redirection method; where less required power is preferred.	W
CR-08	Performance robustness	The ability of the system to resist change, particularly variation in asteroid parameters, where greater robustness is preferred. Robustness with respect to the chemical composition, diameter, density, and rotation rate will be	Coefficient of variation of the delta-v found through Monte Carlo analysis

		considered.	
CR-09	Asteroid alteration	The change in asteroid mass that results from the redirection method from rendez-vous to capture; where less alteration is preferred.	Average mass change from rendez-vous to capture
CR-10	Long-term value	The value of the redirection method over an extended period of time with consideration of *extensibility* and *reusability* (defined below); where greater long-term value is preferred.	Aggregation of long-term value parameters
	System extensibility	*The ability of the system to be extended for future missions (including missions with different primary goals); where greater extensibility is preferred.*	*Scale of ease in extensibility (Low to High)*
	Reusability	*The ability of the system to be extended for future asteroid redirection missions; where greater reusability is preferred.*	*Scale of ease in reusability (Low to High)*

The following subsections provide a generalized approach to evaluating several of the criteria from Table 2. In particular, system cost, mission risk, robustness, asteroid alteration, and long-term value will be discussed.

1. System Cost

The mission cost estimation for each redirection method will follow the standardized NASA single Cost-Estimating-Relationship (CER) QuickCost model, which has been shown to be a conservative estimating tool. The total cost includes cost of development plus one flight unit in calendar year 2010 US Dollars. The total cost formula for the QuickCost model is represented by Eq. (1), and has a standard error of estimate of 41%.[11] An additional 5% is added to the total cost for each year of required mission operations and data analysis, as well as an additional $250M for the launch cost of an Atlas V.[11] Reference 11 further defines the parameters in Eq. (1) and their data range.

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

2. Mission Risk

The risk assessment method follows standard practice in the space sector, leveraging models from Ref. 11 and the Goddard Risk Matrix Standard Scale.[12] The intention of this section is to assess and quantify the technical risk associated with each redirection method. Tables 3 and 4 outline the scales for event likelihood and consequence evaluation. Equation (2) addresses risk aggregation, and Fig. 1 shows the general risk trends associated with event likelihood and consequence (with green representing low risk, yellow representing medium risk, and red representing high risk).

Table 3. Technical likelihood scale (adapted from Table 24-11 in Ref. 11)

Likelihood	**1 - Very Low**	**2 – Low**	**3 - Moderate**	**4 – High**	**5 - Very High**
Technical (Estimated likelihood of not meeting performance requirements)	$P_T \leq 2\%$	$P_T \leq 15\%$	$P_T \leq 25\%$	$P_T \leq 50\%$	$P_T > 50\%$

Table 4. Technical consequence scale (adapted from Table 24-11 in Ref. 11)

Consequence	**1 - Very Low**	**2 – Low**	**3 – Moderate**	**4 – High**	**5 - Very High**
Technical	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)

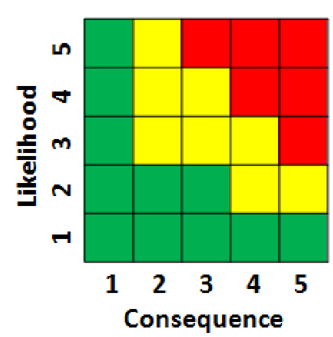


Figure 1. Risk matrix based on NASA standards.[11,12]

The overall expected percentage of objectives returned at the mission end is quantified through the product of likelihood and consequence values for each risk. The following formula describes this relation:[11, 13]

$$E(\%) = 1 - \sum_{i=1}^{n} C(R_i) \times L(R_i) \tag{2}$$

where E is the expected percentage of objectives achieved, C is the consequence value and L is the likelihood value for each risk event R_i. It should be noted that where the consequence and likelihood values are not directly obtainable, estimated values will be attributed through consideration of the relevant literature.

3. Performance Robustness

To determine the robustness of the redirection method, the coefficient of variation, C_v, shown in Eq. (3),will be calculated from the standard deviation of the delta-v, $\sigma_{\Delta v}$, and the average delta-v, $\mu_{\Delta v}$, which are found through a Monte Carlo analysis.

$$C_v = \frac{\sigma_{\Delta v}}{\mu_{\Delta v}} \tag{3}$$

The Monte Carlo analysis will randomly generate values for asteroid diameter, period of rotation, density, enthalpy of sublimation, temperature of sublimation, specific heat, and thermal conductivity within the given ranges specified and according to expected distributions. It should be noted that the period of rotation is chosen with a dependency on the selected diameter, as can be correlated from current asteroid data.[14] The relationship between absolute magnitude, H, and period of rotation, T_{ast}, has been estimated with the following equation.

$$T_{ast} = e^{-0.5091H+11.32} \tag{4}$$

In addition, the Monte Carlo analysis assumes an equal amount of M-Type and C-Type asteroid targets within the sample size. The delta-v and standard deviation are calculated using the standard formulas specified for each method, and therefore, as expected, not all methods will be affected by each variable. A large sample size of 10,000 evaluations is used to ensure the robustness of the Monte Carlo simulation. Table 5 lists the design variables, their ranges and distributions.

Table 5. Monte Carlo parameters and distributions

Category	Parameter	Range	Distribution
Average Diameter	d_{ast}	20-150m	Power law distribution[15]
Period of Rotation	T_{ast}	See Eq. (4) and Fig. 2 (μ_{Trot} = 11.85 ± 0.09hr)	Exponential distribution estimated from Ref. 14
Density	ρ_{ast}	1380±20 kg/m^3 (C-Type) 5320±70 kg/m^3(M-Type)	Gaussian distribution for each type[16]
Enthalpy of Sublimation	E_{sub}	2.75×10^5-1.9686×10^7 J/kg	GCDF determined from Ref.17
Temp. of Sublimation	T_{sub}	1700-1812 K	GCDF determined from Ref.17
Specific Heat	c_a	375-750 J/KgK	GCDF determined from Ref.17
Thermal Conductivity	k_a	0.2-2 W/mK	GCDF determined from Ref.17

4. Asteroid Alteration

The Monte Carlo analysis will also output a mass-loss ratio that relates the mass expelled from the asteroid to the initial asteroid mass. The mass-loss ratio normalizes the change in mass, such that it can be expressed as a percentage change from the initial asteroid mass, as seen in Eq. (5).

$$M_r(\%) = \frac{\Delta m}{m_{ast}} \tag{5}$$

The asteroid alteration parameter will be assessed for appropriate redirection methods by the average mass-loss ratio determined through the Monte Carlo analysis described in the previous section. This parameter will not be calculated for all redirection methods, since their thrust models will negligibly affect the total asteroid mass.

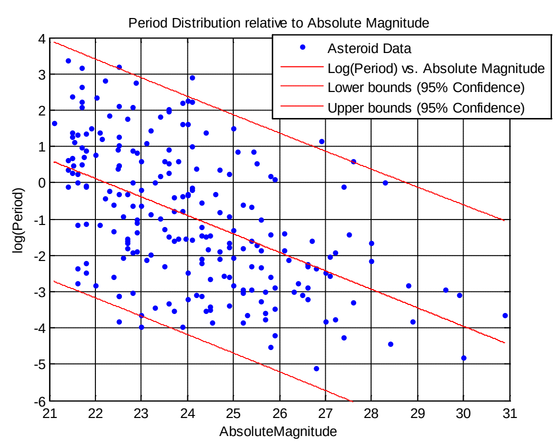


Figure 2. Asteroid period vs. asbsolutemagnitude data[14] with line of best fit and 95% confidence intervals.

5. Long-term Value

The following table will be used to evaluate the long-term value of each redirection method. To assess the long-term value, two criteria have been selected: system extensibility, and reusability. Each redirection method will be allocated a value on the scale provided for each criterion in Table 6. The resulting values will then be averaged to assign an attribute for the long-term value criterion for each redirection method.

Table 6. 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

C. Redirection Methods

The following sub-sections represent the redirection methods considered in this work, with a summary of their major attributes included in section III.

1. Ion Beam

The Ion Beam Shepherd (IBS) applies a highly collimated and high velocity ion beam thrust to the asteroid surface.[18,19,20] A secondary thruster is required to counteract the effects of the beam on the asteroid surface. It has been shown that the gravitational effects of the asteroid can be considered negligible given a hovering distance of approximately twice the asteroid diameter,[19] and as such, it will be assumed that the two thrusters require an equal amount of propellant to maintain the spacecraft's position. Since ion beam thrusters have significant flight heritage, the IBS can be confidently placed in a TRL range of 4-6.[21]

Table 7. Ion beam shepherd criteria summary

Criteria	Value
CR-01 System mass	6800kg (Ref. 19)
CR-02 System volume	$7m^3$(Ref. 19, 23)
CR-03 TRL	4-6 (Ref. 21)
CR-06 System cost	\$602M (Ref. 11)
CR-07 Average required power	10 000W (Ref.22)

The mass of the IBS will be assumed at 6800kg; which is the highest mass given our constraint. The structural mass, m_{str}, will be defined as 300kg, leaving 6500kg of mass for the combination of fuel and power plant. Given the relationship of masses, the force of the thruster can be represented by Eq. (6) as demonstrated in Ref. 18.

$$F_{th} = \frac{(m_{IBS} - m_{str})}{2\left(\frac{\Delta t}{v_e} + \frac{\alpha v_e}{2\eta}\right)} \tag{6}$$

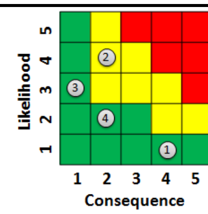
where Δt is the timeframe for redirection, F_{th} is the force of the thruster on the asteroid, α is the inverse specific power (kg/W), η is the thruster efficiency, and v_e is the ejection velocity of the thruster. The state-of-the-art ion thrusters with space flight experience can currently provide a specific impulse of 3300s.[22] However, several more advanced ion propulsion technologies have been considered in the literature with specific impulses as high as 10,000-20,000s.[19] The RIT-XT thruster will be utilized in this model. The RIT-XT is an advanced long-duration space flight ion thruster model designed off of the RIT-10 thruster used on the ARTEMIS and EURECA missions.[22] Based on development models, the nominal power can be taken as 5000W at a nominal specific impulse of 4500s, the thruster efficiency will be set at 60% and the inverse specific power at 10kg/kW.[22] This thruster design will also be utilized in the tugboat and gravity tractor methods for consistency.

Now that the thrusters have been selected and the mass of the fuel is known, the volume of the IBS can be estimated from compressed propellant volume. The optimal compressed density for liquid xenon is 1.35g/ml,[23] which allows us to estimate the total stowed volume of the IBS at $7m^3$ when structural volume is considered. The formula to determine the delta-v for the IBS is presented in Eq. (7), and is dependent on the target asteroid as expected.[18]

$$\Delta V = \frac{3F_{th}\Delta t}{\rho_{ast} d_{ast}^3} \tag{7}$$

Table 8. Ion beam mission risk assessment

CR-05 Mission Risk	Consequence	Likelihood	Matrix
1. Operating lifetime of ion thruster currently tested up to 15000hrs (shorter than mission length).[22]	4	1	
2. Reduced ion beam force on asteroid due to elevated debris interfering with ion beam surface force.[17]	2	4	
3. Reduced fuel directed towards thrusting due to uncertainty in the gravitational field.[24]	1	3	
4. Inconsistent hover distance from asteroid due to uncertainty in the gravitational field effecting net thrust on the asteroid.[24]	2	2	
	E(%) =	**91.45%**	



2. *Tugboat*

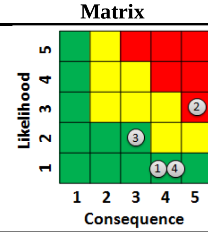
Table 9. Tugboat criteria summary

Criteria	Value
CR-01 System mass	6800kg (Ref. 25)
CR-02 System volume	$10m^3$ (Ref. 23, 25, 26)
CR-03 TRL	4-6 (Ref. 21)
CR-06 System cost	$871M (Ref. 11)
CR-07 Average required power	10000W (Ref. 22)

The tugboat method has been presented many times in the literature in both single and multi-spacecraft configurations. The spacecraft attach to the asteroid surface and provide continuous thrust to ‘push’ the asteroid. The thrust propulsion mechanism ranges amongst references, however for consistency, this work applies the RIT-XT thrusters. This method will consider two spacecraft landing on opposite sides of the asteroid, each with one thruster.[25] The thrusters will be on a gimbal system that enables them to provide continuous redirection thrust without being effected by the asteroid rotation rate. Some versions consider a singular thruster model that lands on the axis of rotation of the asteroid, and first changes the spin vector direction, such that it aligns with the desired thrust direction. However, since this model also requires a gimbal system and has many additional complications, the simpler two spacecraft model has been chosen for this work. The structural mass of the tugboat method is taken to be 500kg, with the total mass of the system at 6800kg. The proposed combined volume of both spacecraft is $10m^3$. This increase in structural mass and volume from the IBS method accounts for the additional lander structural requirements, using the Philae lander as a reference design.[26,27] The tugboat method, similar to the IBS, has a mid-range TRL between 4-6. The tugboat method shares many similar risks to the ion beam method, since they both utilize the same thrusters for exerting force on the asteroid. The requirement to attach to the asteroid surface is one of the greatest risks associated with the tugboat method; however, not orbiting the asteroid does present certain benefits. These benefits include not requiring fuel for station-keeping and greater robustness to the gravitational or geometric uncertainties possible in the asteroid population. Another technical risk associated with this method is the failure of the thruster gimbal system.[26] If a single gimbal fails, the mission could still continue by firing the other thruster when it is within a certain window dictated by the rotation rate. However, the operational limits this would impose on the system would significantly reduce the thrust.

Table 10. Tugboat mission risk assessment

CR-05 Mission Risk	Consequence	Likelihood	Matrix
1. Operating lifetime of ion thruster currently tested up to 15000hrs (shorter than mission length).[22]	4	1	
2. Landing and attachment to the asteroid surface is unsuccessful.[29]	5	3	
3. Asteroid geometry causes a decrease in the available time intervals for providing thrust in the proper direction through the centre of gravity.[24,30]	3	2	
4. Thruster gimbal system failure.[26]	4	1	
	E(%) =	**63.9%**	



3. *Gravity Tractor*

Table 11. Gravity tractor criteria summary

Criteria	Value
CR-01 System mass	6800kg
CR-02 System volume	$7m^3$(Ref. 23)
CR-03 TRL	3-5 (Ref. 21)
CR-06 System cost	$545M (Ref. 11)
CR-07 Average required power	10 000W (Ref. 22)

Through utilizing the mass of the spacecraft or group of spacecraft, a long-term deflection of the asteroid can be achieved through the use of gravitational perturbations. A singular gravity tractor (GT) spacecraft will be considered, and since this method benefits greatly from a large system mass, the maximum permissible mass within the constraints, 6800kg, will be selected. The spacecraft is required to maintain a hover distance through the use of two angled thrusters directed, such that their thrust plume does not counteract the gravity tractor’s pull on the asteroid.[21,31] The GT thrusters will be offset by 20°, half the angle of the exhaust cone, φ, to avoid impinging on the asteroid surface.[21,31] Also, since two RIT-XT thrusters are again used, the gravity tractor system will have a total stowed volume similar to the IBS at 7m^3.[23] The thrust required to maintain a hover distance from the asteroid can now be found by equating it to the asteroids gravitational force. The GT will hover one-half radius above the asteroid surface, similar to in Ref. 31. In the optimal case the hover distance would be adjusted with the change in spacecraft mass. However, in this analysis the hover distance will be held constant. The mass of the gravity tractor over time can be described by Eq. (8) from Ref. 21.

$$m(t) = m_i e^{-\left(\frac{G m_{ast}(t-t_0)}{d^2 \cos\left(\sin^{-1}\left(\frac{r}{d}\right)+\varphi\right) I_{sp} g}\right)} \tag{8}$$

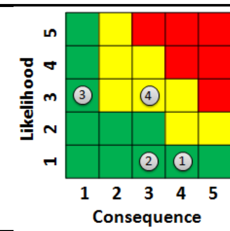
where r is the radius of the asteroid, d is the distance from the centre of mass of the asteroid to the spacecraft, G is the gravitational constant, I_{sp} is the specific impulse, g is the gravity at sea-level and m_i is the initial mass of the spacecraft. The induced acceleration on the asteroid from the gravity tractor can then be found through Eq. (9).[21]

$$a_{gtug}(t) = \frac{Gm(t)}{d^2} \tag{9}$$

Through integration of the induced acceleration formulation, Eq. (9), with respect to the timeframe for redirection, the total delta-v can be resolved. Lastly, the gravity tractor method experiences many of the same risks as the ion beam shepherd, with additional technical risks that result from its thruster exhaust impinging on the asteroid surface.

Table 12. Gravity tractor mission risk assessment

CR-05 Mission Risk	Consequence	Likelihood	Matrix
1. Operating lifetime of ion thruster currently tested up to 15000hrs (shorter than mission length).[22]	4	1	
2. Thruster angle insufficient to ensure exhaust plume does not impinge the surface of the asteroid.[32]	3	1	
3. Additional fuel required for position-keeping due to uncertainty in the gravitational field.[24]	1	3	
4. Inconsistent hover distance from asteroid due to uncertainty in the gravitational field effecting net acceleration induced on the asteroid.[24]	3	3	
	E(%) =	**84.45%**	



4. *Laser Sublimation*

This approach is heavily discussed in literature, and utilizes lasers to sublimate the surface of the asteroid. The sublimated material then generates a thrust on the asteroid affecting its trajectory. Several works can be found that study the effects of the sublimation plumes on both the overall motion of the asteroid and on the lifetime of the spacecraft (for e.g. Ref. 33). In addition, several spacecraft formations have been explored for this method attempting to maximize the lasers effect on the asteroid surface (for e.g. Ref. 34). This work will consider a single laser sublimation spacecraft, based primarily on Ref. 35 and Ref. 36. A comparable laser power system requiring 10kW will be used in this model. From this power system the dry mass, wet mass, and volume of the system can be extrapolated to be 1700kg, 4300kg, and 15m^3, respectively, given the AdAM/Light-Touch2 model.[35] The laser sublimation model applies a thrust on the asteroid by sublimation of material on the asteroid surface. The mass flow rate of the sublimated material, $\dot{m}$, described in Eq. (10), can be determined from a knowledge of the velocity of the asteroid as it travels through the illuminated spot area, v_{rot}, the latent heat of complete sublimation, E_v, the height of the spot [y_{min}, y_{max}], the duration for which the spot is illuminated [t_{in}, t_{out}], the absorbed laser power per unit area, P_I, the heat loss per unit area through radiation, Q_{RAD}, the heat loss per unit area through conduction, Q_{COND}, the ejecta velocity, $\bar{v}$, the heat capacities, c_p and c_v, the sublimation temperature, T_{sub}, and the temperature of the material prior to sublimation, T_0.[36]

Table 13. Laser sublimation criteria summary

Criteria	Value
CR-01 System mass	4300 kg (Ref. 35)
CR-02 System volume	15m^3 (Ref. 35)
CR-03 TRL	2-3 (Ref. 21)
CR-06 System cost	$1.46B (Ref. 11)
CR-07 Average required power	10000W

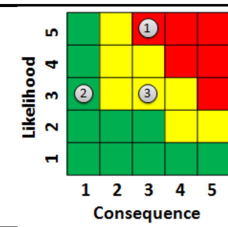
$$\dot{m} = 2v_{rot}\int_{y_{min}}^{y_{max}}\int_{t_{in}}^{t_{out}} \frac{1}{\left(E_{sub} + \frac{1}{2}\bar{v}^2 + c_p(T_{sub} - T_0) + c_v(T_{sub} - T_0)\right)}(P_I - Q_{RAD} - Q_{COND})\,dydt \tag{10}$$

It should be made explicit that this work does not consider degradation of the absorbed laser power due to the effects caused by deposited re-condensed ejecta material. The works of Ref. 17 and Ref. 36 provide a more in-depth analysis of the degradation factor from the Beer-Lambert-Bougier-Law as well as additional details on the laser-sublimation approach. The laser system utilized in this model was taken to have an efficiency of 50%,[17] a spot size of 1mm,[36] and an absorption of the laser beam within the plume of a conservative 10%.[36] The procedure for determining the absorbed power, heat loss due to radiation, heat loss due to conduction, and the average velocity of the ejecta plume can be found in Ref. 36. Equation (11) is used to determine the delta-v of the laser sublimation method, where F_{sub} is the force of sublimation, $m_{ast}(t)$ is the time-dependent mass of the asteroid, and $[t_i, t_f]$ represents the redirection timeframe.[36]

$$\Delta V = \int_{t_i}^{t_f} \frac{F_{sub}}{m_{ast}(t)} dt \tag{11}$$

The force of sublimation can be found from the product of the mass flow rate, the average velocity of the ejecta, and the scatter factor, $\lambda = 2/\pi$ (which represents a uniform distribution over a half sphere).[17,36] It should be noted that if the degradation factor had been considered in this work, the mass flow rate would also be time dependent. The omission of this degradation factor has been accounted for through the addition of a technical risk particular to thrust degradation due to the depositing of re-condensed ejecta.

Table 14. Laser sublimation mission risk assessment

CR-05 Mission Risk	Consequence	Likelihood	Matrix
1. Thrust degradation due to deposited re-condensed ejecta material.[17]	3	5	
2. Additional fuel required for position-keeping due to uncertainty in the gravitational field.[24]	1	3	
3. Inconsistent hover distance from asteroid due to uncertainty in the gravitational field effecting net acceleration induced on the asteroid.[24]	3	3	
	E(%) =	37.25%	

5. Mass Ejector

Table 15. Mass ejector criteria summary

Criteria	Value
CR-01 System mass	6800kg (Ref. 37)
CR-02 System volume	120 m^3 (Ref. 37)
CR-03 TRL	3 (Ref. 21)
CR-06 System cost	$2.30B (Ref. 11)
CR-07 Average required power	82 000 W (Ref. 37)

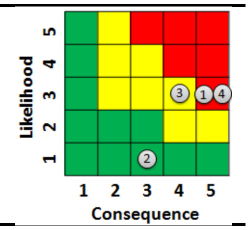
The mass ejector method employs a drilling mechanism on the surface of the asteroid to extract asteroid material which it then launches to generate a thrust on the asteroid. Mass ejectors are frequently utilized in formations in order to maximize material extraction and to negate the effects of rotation rate on the method. The model used in this comparison is a singular spacecraft that is heavily based on the Modular Asteroid Deflection Mission Ejector Node or 'MADMEN'concept.[37]The mass ejector spacecraft is equipped with both a large extraction mechanism and a rail gun for launching extracted asteroid mass. The dry mass of the system will be set to 6800kg in order to maximize the mass of the power system, m_{power}, that is expected to be equal to about 30% of the dry mass.[37]Given the increased mass from the MADMEN model, a stowed volume of 120m^3 can be estimated from assuming an increased lander base diameter of 4.5m, and a deployable rail length of 15m that can be stowed at half the length. Also, given the scaled mass of the power system, a high power demand of 82kW is expected, which is fairly comparable to the power demands for MADMEN if scaled.[37]A 30% rail gun efficiency is used to determine the power of the system converted to kinetic energy. From the power converted to kinetic energy, the mass-to-power ratio (taken to be 25 kg/KW)[21] and the ejection velocity, v_e, which is conservatively taken to be 200 m/s,[21,37] the mass of each projectile and timeframe available for ejection can be established, according to the procedure specified in Ref. 37. The available time period to eject the extracted mass is dependent on the period of rotation of the asteroid, since the mass ejector can only fire in a ±5° window of the desired thrust direction.[37] Furthermore, it is assumed that the mass ejector can mine a sufficient amount of mass during each rotation to maintain a consistent launch mass, and that the ejector launches once per asteroid rotation. However, if the rotation rate is faster than 1rev/min, then the mass ejector is assumed to launch no more than one projectile per minute. The finite delta-v can then be calculated for each mass launched using Eq. (12).[21]

$$\delta v = \frac{m_{launch}}{m_{ast}(t)} v_e \tag{12}$$

The total delta-v from all the mass launched can be determined by the summation of all the finite shot delta-v's over the given redirection timeframe.

Table 16. Mass ejector mission risk assessment

CR-05 Mission Risk	Consequence	Likelihood	Matrix
1. Landing and attachment to the asteroid surface is unsuccessful.[29]	5	3	
2. Asteroid geometry causes a decrease in the available time intervals for providing thrust in the proper direction through the centre of gravity.[24,30]	3	1	
3. Drill unable to mine sufficient mass to eject.[35]	4	3	
4. Dust deposits collecting on lander disabling operation.[38]	5	3	
	E(%) =	26.25%	



6. *Other Redirection Methods*

The following methods are considered for asteroid mitigation, but are not suitable for asteroid redirection: kinetic impactor,[39] solar sail,[40] painting,[41] tether and ballast,[42] nuclear explosion,[43]electrostatic field,[44] and magnetic flux compression.[45] Several of these methods, such as the solar sail and painting approaches, require long timeframes for redirection that are outside of the scope of this work. Moreover, the electrostatic field and magnetic flux compression approaches have a TRL lower than 2, which places them outside of the scope of this work. The tether and ballast approach is omitted due to long timeframes for redirection as well as large volume and mass requirements. The kinetic impactor approach is a good candidate for deflection, but not for safe redirection due to the lack of controllability of a single impact method. Similarly, the nuclear explosion approach, which is one of the most viable approaches for deflection, has been omitted due to its lack of controllability as well as the destructive nature of this method. Since the aim of this work is asteroid redirection for the purpose of resource exploitation, the nuclear explosion approach has been excluded from the assessment. Lastly, several solar concentrated sublimation approaches are considered in the literature for asteroid deflection that have potential to be good candidates for asteroid redirection. However, upon further inspection, it becomes clear that the solar collectors required for such methods are very large and require technologies with TRLs too low to be feasible within the constraints.[46] The most viable solar concentrated sublimation method utilizes a solar-pumped laser system,[46] and given the similarity of this method to the laser sublimation approach, it has been omitted from this work.

7. *Attributes Determined from Monte Carlo Analysis*

Table 17 presents the average delta-v, standard deviation, and standard error for each redirection method. Moreover, the performance robustness attribute is represented in the table by the coefficient of variation for each method. As expected, the ion beam and tugboat approaches have near equivalent robustness with regards to variation in asteroid parameters, due to the similarity of their thrusting mechanisms. The laser sublimation approach has the most considerable variation, due to its dependence on the chemical composition of the asteroid.

Table 17. Delta-V and performance robustness parameters

	ΔV_{ave} [km/s]	$\sigma_{\Delta V}$	Standard Error	C_v
RM-01 Ion Beam Shepherd	0.0079	0.0094	9.3666×10^{-5}	1.18
RM-02 Tugboat	0.0154	0.0182	1.8157×10^{-4}	1.18
RM-03 Gravitational Tractor	6.1260×10^{-8}	4.6049×10^{-8}	4.6049×10^{-10}	0.75
RM-04 Laser Sublimation	4.1632×10^{-5}	1.1238×10^{-4}	1.1238×10^{-6}	2.70
RM-05 Mass Ejector	0.0418	0.0649	6.4901×10^{-4}	1.55

The asteroid alteration attributes for each redirection method are summarized in Table 18. The first three methods were assigned a mass-loss ratio value of zero due to negligible impact on the asteroid surface over the transfer duration, from rendez-vous to capture. The mass ejector method shows an average mass-loss ratio of 15% from the Monte Carlo analysis. This value is quite significant, and the percentage mass-loss can increase significantly for asteroids with small diameters. Overall, the mass ejector affects mass retention considerably more than any of the other redirection methods. A notable change in mass was also expected from the laser sublimation method, since it depends on mass removal to generate thrust. However, the mass loss from the laser sublimation method showed a total change in mass much smaller than

Table 18. Asteroid alteration values

CR-09 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	0.01295%	3.4912×10^{-4}	3.4912×10^{-6}
RM-05 Mass Ejector	15.46%	0.0649	6.4901×10^{-4}

anticipated. The low mass-loss ratio can be attributed to the effect of fast surface rotation velocities innate to the small asteroid population. This increased rotational velocity reduced the sublimation time available, decreasing the mass flow rate, and hence reducing the total sublimated mass. For this same reason the average delta-v was also considerably reduced, especially when the rotation rate did not allow for sufficient time to induce sublimation. 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 able to induce a sublimation thrust on the asteroid.

8. Long-term Value of Redirection Methods

The long-term value of each redirection method was assessed by evaluating its potential for system extensibility and reusability. These parameters can be assigned by determining the possible operational lifetime of the methods' critical component,[17,22,37] as well as considering the particular functional design of the system.

Table 19. Long-term value table

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**

D. Aggregation Method

The attributes assigned to the criteria for each redirection method will be aggregated using the utility-based decision making method.[47] The method uses a pairwise weighting mechanism for comparing multiple criteria in order to rank various options. The criteria that will be assessed are the same as those presented in II.B. These criteria will now be weighted through the aggregation of scores from pairwise comparisons of the criteria. The scoring system ranges linearly from 1 to 9, and can be found in Ref. 48; where a value of 1 indicates equal importance and 9 indicates extreme importance of one criterion over another.

Three weightings will be established from the pairwise comparisons, i.e. cost-based (risk seeking), balanced, and performance-based (risk averse). The cost-based assessment will highly value the delta-v and cost parameters, while attributing lowers values to the TRL, mission risk, asteroid alteration, and robustness parameters. Such weighting represents an investor who may be risk seeking, hence looking for the mission with the maximum return in asteroid material at the lowest cost. Conversely, the performance-based weighting can be considered similarly to a risk averse investor, since it highly weighs the TRL, mission risk, asteroid alteration, and robustness parameters, while less valuing the delta-v and cost parameters. This weighting suggests the investor is more concerned with a successful mission, and is willing to accept a lower return as a result. A balanced weighting has also been constructed that weighs the criteria between the two extremes presented. Given the pairwise comparisons for each scoring presented in Tables 20, 21, and 22, the weight for each parameter can be determined by the summation of each row and then the normalization of the sums. The differences in scoring for the cost-based and performance-based approaches have been highlighted in green or red, denoting an increase or a decrease, respectively, from the balanced weighting. The normalized criteria weighting for the cost-based, balanced, and performance-based approaches are summarized in Table 23.

Table 20. Criteria relative importance for the balanced approach

ID	Criteria	CR-01	CR-02	CR-03	CR-04	CR-05	CR-06	CR-07	CR-08	CR-09	CR-10	Total
CR-01	System mass	1	2	1/3	1/7	1/5	1/5	1	1/4	1/2	4	**9.626**
CR-02	System volume	1/2	1	1/5	1/7	1/5	1/5	1/2	1/4	1/3	3	**6.326**
CR-03	TRL	3	5	1	1/3	1/2	1/3	2	1/2	1/2	2	**15.167**
CR-04	Delta-V	7	7	3	1	2	3	7	4	5	8	**47**
CR-05	Mission risk	5	5	2	1/2	1	1/2	5	2	3	5	**29**
CR-06	System cost	5	5	3	1/3	2	1	6	3	3	8	**36.333**
CR-07	Power	1	2	½	1/7	1/5	1/6	1	1/4	1/3	3	**8.593**
CR-08	Robustness	4	4	2	1/4	1/2	1/3	4	1	1	5	**22.083**
CR-09	Asteroid alteration	2	3	2	1/5	1/3	1/3	3	1	1	6	**18.867**
CR-10	Long-Term Value	1/4	1/3	1/2	1/8	1/5	1/8	1/3	1/5	1/6	1	**3.233**

Table 21. Criteria relative importance for performance-based approach

ID	Criteria	CR-01	CR-02	CR-03	CR-04	CR-05	CR-06	CR-07	CR-08	CR-09	CR-10	Total
CR-01	System mass	1	2	1/5	1/5	1/7	1/3	1	1/6	1/4	4	**9.293**
CR-02	System volume	1/2	1	1/7	1/5	1/7	1/3	1/2	1/6	1/5	3	**6.186**
CR-03	TRL	5	7	1	1	1/2	1	4	1/2	1/2	4	**24.5**
CR-04	Delta-V	5	5	1	1	1/2	3	5	2	3	6	**31.5**
CR-05	Mission risk	7	7	2	2	1	2	7	2	3	7	**40**
CR-06	System cost	3	3	1	1/3	1/2	1	4	1	1	6	**20.833**
CR-07	Power	1	2	1/4	1/5	1/7	1/4	1	1/6	1/5	3	**8.210**
CR-08	Robustness	6	6	2	½	1/2	1	6	1	1	7	**31**
CR-09	Asteroid alteration	4	5	2	1/3	1/3	1	5	1	1	8	**27.667**
CR-10	Long-Term Value	1/4	1/3	1/4	1/6	1/7	1/6	1/3	1/7	1/8	1	**2.911**

Table 22. Criteria relative importance for cost-based approach

ID	Criteria	CR-01	CR-02	CR-03	CR-04	CR-05	CR-06	CR-07	CR-08	CR-09	CR-10	Total
CR-01	System mass	1	2	1	1/9	1/3	1/7	1	1/2	2	4	**12.087**
CR-02	System volume	1/2	1	1/3	1/9	1/3	1/7	1/2	1/2	1	3	**7.421**
CR-03	TRL	1	3	1	1/5	1/2	1/5	1/2	1/2	1/2	1/2	**7.9**
CR-04	Delta-V	9	9	5	1	4	3	9	6	7	9	**62**
CR-05	Mission risk	3	3	2	¼	1	1/4	3	2	3	3	**20.5**
CR-06	System cost	7	7	5	1/3	4	1	8	5	5	9	**51.333**
CR-07	Power	1	2	2	1/9	1/3	1/8	1	1/2	1	3	**11.069**
CR-08	Robustness	2	2	2	1/6	1/2	1/5	2	1	1	3	**13.867**
CR-09	Asteroid alteration	1/2	1	2	1/7	1/3	1/5	1	1	1	4	**11.176**
CR-10	Long-Term Value	1/4	1/3	2	1/9	1/3	1/9	1/3	1/3	1/4	1	**5.056**

Table 23.Normalized criteria weights

ID	Criteria	Performance (Risk Averse)	Balanced	Cost-Based (Risk Seeking)
CR-01	System mass	0.046	0.049	0.060
CR-02	System volume	0.031	0.032	0.037
CR-03	Technology readiness level (TRL)	0.121	0.077	0.039
CR-04	Delta-V	0.156	0.240	0.306
CR-05	Mission risk	0.198	0.148	0.101
CR-06	System cost	0.103	0.185	0.254
CR-07	Average required power	0.041	0.044	0.055
CR-08	Performance Robustness	0.153	0.113	0.068
CR-09	Asteroid alteration	0.137	0.096	0.055
CR-10	Long-Term Value	0.014	0.016	0.025

III. Results and Discussion

This section contains the results from the weighted aggregation with respect to the criteria for each redirection method. In particular, in Table 24, a summary of attributes for each redirection method is presented, followed by a normalization of these values in Table 25. The attribute normalization follows a linear scale, where the most preferred value for each criterion is assigned a value of 100 and the least preferred value is assigned a zero. The remaining attributes are normalized according to a linear scale between the assigned most and least preferred values. Also, if a TRL range was assigned to a redirection method, the average value was considered during normalization.

Table 24. Summary of attributes

ID	Criteria	RM-01	RM-02	RM-03	RM-04	RM-05
CR-01	System mass (kg)	6800	6800	6800	4300	6800
CR-02	System volume (m^3)	7	10	7	15	120
CR-03	TRL	4-6	4-6	3-5	2-3	3
CR-04	Delta-V (km/s)	0.0079	0.0154	6.1260×10^{-8}	4.1632×10^{-5}	0.0418
CR-05	Mission risk (%)	91.45	63.9	84.45	37.25	26.5
CR-06	System cost ($)	602M	871M	545M	1.46B	2.30B
CR-07	Power (kW)	10	10	10	10	82
CR-08	Robustness	1.18	1.18	0.75	2.70	1.55
CR-09	Asteroid Alteration (%)	0%	0%	0%	0.01295%	15.46%
CR-10	Long-Term Value	4	1.5	4	2.5	1

Table 25. Normalized attributes

ID	Criteria	RM-01	RM-02	RM-03	RM-04	RM-05
CR-01	System mass	0	0	0	100	0
CR-02	System volume	100	97.34	100	92.92	0
CR-03	TRL	100	100	60	0	20
CR-04	Delta-V	18.9	36.8	0	0.0994	100
CR-05	Mission risk	100	57.58	89.22	16.55	0
CR-06	System cost	96.75	81.42	100	47.86	0
CR-07	Power	100	100	100	100	0
CR-08	Robustness	78	78	100	0	59
CR-09	Asteroid alteration	100	100	100	99.92	0
CR-10	Long-Term Value	100	37.5	100	62.5	0

Table 26 presents the results from the aggregation for each redirection method with respect to the three different weighting mechanisms, i.e. performance-based, balanced, and cost-based approaches; and Fig. 3 shows the results in the form of a bar graph.

Table 26. Weighted aggregation results

ID	Method	Performance-Based	Balanced	Cost-Based
RM-01	Ion Beam Shepherd	79.0	72.5	66.9
RM-02	Tugboat	70.9	66.6	62.5
RM-03	Gravitational Tractor	72.8	66.4	60.8
RM-04	Laser Sublimation	34.4	34.2	35.8
RM-05	Mass Ejector	27.0	32.2	35.4

The results of the analysis indicate that the ion beam shepherd, tugboat, and gravity tractor methods are generally more favourable than the laser sublimation and mass ejector approaches. In particular, the ion beam shepherd returns the highest values across all three weightings. This demonstrates that the ion beam shepherd is generally an attractive method, regardless of investor preference. The tugboat and gravity tractor methods are also very strong candidates for a redirection mission, with overall performance lower than, but comparable to, the ion beam shepherd. These two methods have very similar aggregation values to one another across all three weightings, and are near equality for the balanced weighting. The ion beam shepherd outperforms the gravity tractor notably with respect to the delta-v criterion, and it has a significantly lower mission risk than the tugboat approach. These two criteria are generally heavily weighted across all three scoring approaches and may account for some of the disparity between the ion beam shepherd and the next highest candidate methods.

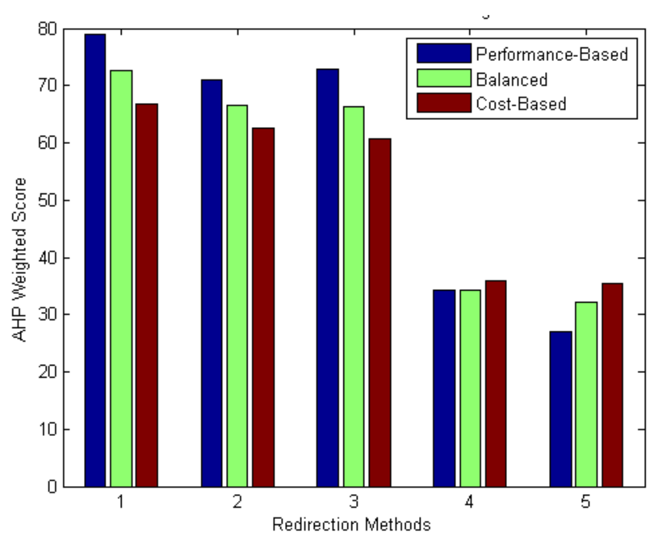


Figure 3. Redirection method scores for each weight scenario.

The laser sublimation and mass ejector methods demonstrated low performance across all three aggregation scenarios. The mass ejector performed the worst overall of all the methods. Despite having the highest delta-v value, its performance across many of the other criteria was very weak. In particular, it scores considerably low with respect to power, cost, and asteroid alteration; receiving the lowest normalized value for seven of the ten assessment criteria. Although it does not perform well for a resource exploitation mission, it may have potential if maximizing delta-v is the only mission concern. The laser sublimation approach was also significantly outperformed by the ion beam, tugboat, and gravity tractor methods. The laser sublimation method's high dependence on uncertain asteroid parameters provides an insecure investment with a low delta-v return. It is possible that with a spacecraft formation approach the performance of this redirection method could be considerably improved.

The assessment also clearly distinguishes the high risk methods from the low risk methods. The laser sublimation and mass ejector methods, which have the lowest TRLs and highest mission risk, perform considerably better in the cost-based (risk seeking) approach than in the performance-based (risk averse) approach. Conversely, the ion beam, tugboat, and gravity tractor methods demonstrate better results in the performance-based scenario. This provides further insight into the potential applicability of each method to different investor types.

IV. Conclusions

This work has provided a framework for the assessment of redirection methods from the perspective of resource exploitation. The five redirection methods considered were defined for singular or dual spacecraft configurations, reasonably constrained, and assessed according to key mission criteria. The methods were evaluated with respect to the expected small asteroid population through a Monte Carlo analysis that demonstrated their capabilities across several parameters. The attributes for each redirection method were then aggregated using three different weighting scenarios. The aggregation results showed considerable preference to the ion beam shepherd, tugboat, and gravity tractor methods over the laser sublimation and mass ejector approaches. In future works, a consistency and sensitivity analysis should be performed to validate these conclusions, as well as further investigations utilizing more sensitive multi-criteria aggregation techniques. Moreover, the effect, applicability, and potential advantages of spacecraft formation strategies for each of the redirection methods could provide greater insight into their viability for a redirection mission.

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