BIS-RS-2019-04

Influence of Launcher Cost and Payload Capacity on Asteroid Mining Profitability

Merel Vergaaij
merel.vergaaij@glasgow.ac.uk

Colin McInnes
colin.mcinnes@glasgow.ac.uk

Matteo Ceriotti
matteo.ceriotti@glasgow.ac.uk

James Watt School of Engineering, University of Glasgow
Glasgow, G12 8QQ, United Kingdom

ABSTRACT

A range of resources can be extracted from asteroids, for example volatiles for propellant and consumables for (crewed) spacecraft, semi-conductors and metals for in-space manufacturing or platinum group metals for terrestrial use. One of the key justifications for in-situ manufacturing/resource utilisation is the high costs incurred during launch from the Earth's deep gravity well. However, selling asteroid-derived resources in Earth orbit at a price competitive with launching the same resources from the Earth's surface is largely dependent on specific launch costs, especially for low value-to-mass resources such as volatiles and construction materials. This paper investigates the influence of the cost and payload capacity of launch vehicles on asteroid mining profitability. Results demonstrate that for resources delivered to GEO, if the launch cost decreases, the specific launch cost (per kg) decreases in such a way that the decrease in total cost is smaller than the decrease in revenue, resulting in a less profitable mission. Similarly, when the payload capacity increases and therefore the specific launch cost decreases, the resulting mission also generates less profit. Sensitivity analyses show that for an example mission with two round trips to the same asteroid, profits increase with the increased number of trips, if the asteroid has not been fully depleted. Similarly, a further sensitivity analysis demonstrates that by changing the destination orbit for the processed resources to the Lunar Gateway, increased profit margins can be realised.

KEYWORDS: Asteroid mining, Economic modelling, Trajectory optimisation, Launch vehicles, Net Present Value.

INTRODUCTION

Interest in asteroid mining missions has grown in recent years, with a number of companies emerging on the global market.[1] It is recognised that asteroid mining could provide a long-term solution to alleviating shortages of easily-accessible key natural resources on Earth, on which sustainable technology development is dependent. Moreover, asteroid resources could provide bulk material in (Earth) orbit, for example for propellant for crewed deep space exploration missions or material for the fabrication of space-based habitats.[2–6]

Many important issues for the success of asteroid mining missions are being addressed: classification of near-Earth asteroids (NEAs),[7] trajectory optimisation to and from NEAs,[8–13] mining equipment[14–16] and economic modelling of these missions.[4–6,17,18]

For economic modelling, many assumptions must be made concerning a range of elements of the mission. One such elements is the launch vehicle, with assumptions on payload capacity and launch cost. While one of the key justifications for the utilisation of asteroid resources is the high costs otherwise incurred if the same resources were to be launched from Earth, the effect of decreasing launch costs and increasing payload capacity is not yet fully understood. With current trends in launch vehicle development, this is an important issue to investigate. Therefore, this paper aims to investigate the influence of launch vehicle cost and payload capacity on the economic profitability of asteroid mining missions.

First, a top-level mission architecture is defined. Next, a methodology to investigate the impact of launch cost and payload capacity is established, which includes the coupling of economic modelling and trajectory optimisation. Two case studies are presented and the methodology is subsequently applied to derive general relationships between the launch vehicle characteristics and the profitability of an asteroid mining mission. Several sensitivity analyses are performed: a mission scenario with two round-trips instead of one, selling resources at the Lunar Gateway instead of GEO and a set of Monte Carlo simulations to investigate the sensitivity of the results to certain input parameters.

MISSION ARCHITECTURE

A schematic for the mission concept proposed in this paper, similar to the mission assessed in Reference [6], is presented in Figure 1. For all missions investigated, the mission starts by a launch to LEO, for which an altitude of 185 km is assumed based on SpaceX launches.[19] The launcher is used at its maximum payload capacity with a kick-stage, a cargo spacecraft and the mining and processing equipment (MPE). For ease of comparison, from LEO the kick-stage transfers the payload (cargo spacecraft and MPE) to an escape trajectory with $C_3 = 0$ km^2/s^2. At escape, the cargo spacecraft, carrying the MPE, departs on a high-thrust Lambert arc to a target NEA,[20] which is assumed to be C-type with water resources. Upon arrival at the asteroid, the MPE is placed on the asteroid and mining and

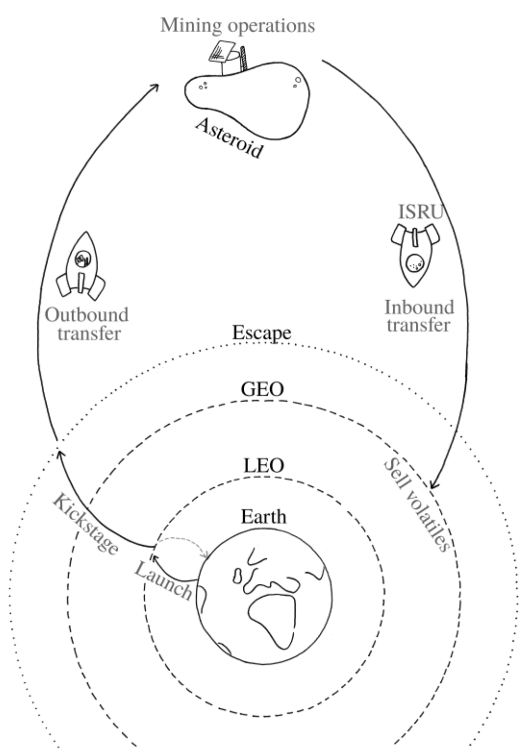

Figure 1. Mission Schematic Overview.

processing commences. A key parameter for the mission is the throughput of the MPE, defined as the resource mass per unit time delivered per unit mass of MPE. The duration of the mining phase will therefore determine the total mass of resources that can be acquired and then transported to Earth. At the end of the mining phase, the cargo spacecraft returns to Earth using a Lambert transfer to geostationary orbit (GEO). During the transfer, the cargo spacecraft makes use of a fraction of the mined propellant. In GEO, the remaining resources (e.g. remaining propellant) are sold at a price which must be competitive with launching the same resources from Earth.

METHODOLOGY

The paper combines trajectory optimisation and economic modelling, both of which are discussed in this section.

The Net Present Value (NPV) has been identified as a useful metric for assessing the economic viability of asteroid missions,[1,3–6,18] and is therefore used here. This section will firstly elaborate on the definition of the mass budget for the mission and the resource mass to be delivered to GEO. Then, the specific methodology for the economic modelling is detailed, followed by the trajectory optimisation strategy and target selection.

Mass Budget Calculation

This section describes the method used for calculating the mission mass budget and other key parameters that characterise the mission defined by the top-level concept shown in Figure 1.

The payload capacity of the launcher to LEO m_{LEO} (at 185 km altitude) is equal to:

$$m_{LEO} = m_{ks} + m_{s/c,wet} \tag{1}$$

where m_{ks} is the wet mass of the kick stage to reach escape and $m_{s/c,wet}$ the total wet mass of the composite spacecraft delivered en-route to the asteroid:

$$m_{sc,wet} = m_{cargo} + m_{MPE} + m_{prop}^{O} \tag{2}$$

where m_{cargo} is the dry mass of the cargo spacecraft, m_{MPE} is the mass of the MPE and m_{prop}^{O} is the propellant mass required for the outbound transfer.

Using m_{LEO}, first the mass of propellant for the kick-stage $m_{ks,prop}$ is calculated using:

$$m_{ks,prop} = m_{LEO}\left(1 - e^{-\frac{\Delta V_{LEO\to escape}}{I_{sp}g_0}}\right) \quad (3)$$

where $\Delta V_{LEO\to escape}$ is the ΔV required to transfer from LEO to an Earth escape trajectory and I_{sp} is the specific impulse of the propulsion system (446 s for the LOX/LH2 combination considered here[21]). In combination with the minimum structural mass coefficient $\epsilon_{min} = 0.1$, $m_{ks,prop}$ this can be used to calculate the dry mass of the kick stage as:

$$m_{ks,dry} = \frac{\epsilon_{min}}{1 - \epsilon_{min}} m_{ks,prop} \quad (4)$$

The remainder of the launch vehicle payload capacity ($m_{s/c,wet}$), comprising the cargo spacecraft, propellant and MPE will then depart on a Lambert arc starting from the escape trajectory with $C_3 = 0$ km^2/s^2, again for ease of comparison. The propellant mass required for the outbound transfer will depend on the ΔV associated with this Lambert arc, ΔV^O, for the outbound transfer such that:

$$m_{prop}^O = m_{s/c,wet}\left(1 - e^{-\frac{\Delta V^O}{I_{sp}g_0}}\right) \quad (5)$$

From this result, the total dry mass arriving at the asteroid can be calculated as:

$$m_{s/c,dry} = m_{s/c,wet} - m_{prop}^O \quad (6)$$

Using a mass fraction λ_{MPE}, to be optimised later, the spacecraft dry mass is divided into m_{MPE} and m_{cargo} where:

$$m_{MPE} = \lambda_{MPE} m_{s/c,dry} \quad (7a)$$

$$m_{cargo} = (1 - \lambda_{MPE}) m_{s/c,dry} \quad (7b)$$

The mass of resources that are mined and processed at the asteroid is determined by m_{MPE}, the duration of the mining phase (t_{mining}) and the throughput rate (r) in kg/day per kg of MPE, such that:

$$m_{r,mined} = m_{MPE}\, r t_{mining} \quad (8)$$

where t_{mining} is defined by:

$$t_{mining} = t_{stay} - 14 \text{ days} \quad (9)$$

where 14 days are allocated for proximity operations, placing the MPE on the asteroid and the final resource transfer to the cargo spacecraft for return to Earth.

The throughput rate r to mine water and process it into LH2 and LOX is calculated using a relatively conservative[16] initial throughput of 200 kg/day per kg of MPE. This includes the equipment necessary for collecting and grinding, separating gases from solids and condensing vapours.[14] Reference [14] suggests 1500 kg can be allocated for these elements of the equipment, which therefore means a mass flow rate of 300,000 kg/day, or 3.47 kg/s. In addition to this equipment mass, the mass of the power system for mining water and electrolysing the water into LOX/LH2, along with the mass of the required structure, heat engine and compressors must be added. Reference [14] suggests a structural mass of 300 kg, a compressor mass of 10 kg, a heat engine mass of 100 kg and a power requirement of 200 kW for the above mass flow rate. In the mid- to far-term, solar array performance is envisioned to reach 4 kg/kW.[22] The power requirement for the electrolysis is estimated using the Gibbs free energy of water for dissociation into H_2 and O_2 which is 13.16 MJ/kg.[23] Using the mass flow rate determined above, the power requirement for electrolysis can be estimated, followed by the required solar array mass. It is assumed that cooling of the gases to liquid is performed by simply directing flow pipes into shadow, while providing sufficient heat transfer to cold space.[15] Subsequently, a 10% margin is added to the total system mass to account for uncertainties. Finally, using the mass flow rate and the total system mass, the throughput rate, r, can be estimated as 1.47 kg/day per kg of MPE.

While the mining and processing equipment may be able to produce a certain quantity of LOX/LH2, the total mass that can be transported (m_r) is constrained by both the maximum volatile mass available at the asteroid, and the maximum mass that can be transported by the cargo spacecraft.

The total volatile mass available from the target asteroid is approximated using the absolute magnitude of the asteroid (H), the average geometric albedo for C-type asteroids ($p_{v_C} = 0.06$) [24] and the average density of C-type asteroids ($\rho_C = 1300$ kg/m^3),[24] along with an expected volatile recovery ratio of $\lambda_{volatile} = 10\%$.[3] First, the diameter of the (assumed spherical) asteroid can be approximated using:[24]

$$D[\text{km}] = 1329 \frac{10^{-\frac{H[-]}{5}}}{\sqrt{p_{v_c}[-]}} \quad (10)$$

from which the total available volatile mass can be estimated as:

$$m_{r,available} = \frac{\pi}{6} D^3 \rho_C \lambda_{volatile} \quad (11)$$

A minimum structural mass coefficient $\epsilon_{min} = 0.1$ will be assumed for the cargo vehicle,[25] so that the total mass that can be transported using the cargo spacecraft is determined as:

$$m_{r,transportable} = \frac{1 - \epsilon_{min}}{\epsilon_{min}} m_{cargo} \quad (12)$$

Finally, the propellant mass m^I_{prop} required for the inbound Lambert arc determines the resource mass $m_{r_{GEO}}$ that can be delivered and sold in GEO such that:

$$m^I_{prop} = (m_{cargo} + m_r) \times \left(1 - e^{-\frac{\Delta V^I + \Delta V_{escape\rightarrow GEO}}{I_{sp} g_0}}\right) \quad (13a)$$

$$m_{r_{GEO}} = m_r - m^I_{prop} \quad (13b)$$

where ΔV^I is the ΔV required for the inbound Lambert arc and $\Delta V_{escape\rightarrow GEO}$ is the ΔV required for the final transfer from Earth escape energy at arrival to GEO.

Economic modelling

For any project the NPV takes into account the forgone interest that funds could have been earning if they were invested in an alternative venture: the longer the wait for income, the less present worth it has, and the more heavily discounted it should be.[5] The NPV considers costs and revenues over time and calculates the present worth of a project such that:

$$NPV = \sum_{t=1}^{N} \frac{R_t - C_t}{(1 + I)^t} \quad (14)$$

where R_t is the revenue generated at time t, C_t the costs incurred at time t and I is the discount rate per unit time (i.e., the return that could be generated per unit time on an investment with similar risk). For a single asteroid mining mission where all costs are paid upfront and all revenue is generated at the end of the mission, Eq. (14) is simplified to:

$$NPV = \frac{R}{(1 + I)^t} - C_0 \quad (15)$$

For the mission architecture defined in the previous sections, Eq. (15) is expanded to:

$$NPV = \frac{p m_{r_{GEO}}}{(1 + I)^{t_{mis}}} - (C_{dev} + C_{man}) m_{s/c,dry} - C_{prop}\, m^O_{prop} - C_{ks,escape} - C_l - C_{op} t_{mis} \quad (16)$$

where C_{dev} is the project development cost, C_{man} is the manufacturing cost, C_{prop} is the propellant cost, all per kg. Moreover, $C_{ks,escape}$ is the cost for the kick stage to escape (including propellant), C_l is the launch cost, C_{op} is the operation cost per year, p is the market price of the returned resources to customers in GEO per kg of resource material and t_{mis} is the total mission duration in years.

Values for the cost elements are given in Table 1. It is assumed that the mission takes place in a mid- to far-term timeframe, thus suggesting that the relevant technologies have been matured through intermediate missions. A rationale for the values for C_{dev}, C_{man}, C_{op} and C_{prop} is given in Reference [6]. Both $C_{ks,escape}$ and p are dependent on m_{LEO}, the payload capacity of the launch vehicle to LEO. In addition, p is also dependent on C_l, as the price the resources are sold at must be competitive with the cost if the same material is launched directly from the Earth's surface:

$$p = p' + C_{l,orbit} \quad (17)$$

where p' is the cost of the materials purchased from terrestrial sources (in this case equal to C_{prop}, considering the low value-to-mass of volatiles) and $C_{l,orbit}$ is the launch cost to the orbit where the resources are sold. To be consistent with the asteroid mining mission concept, $C_{l,orbit}$ includes a launch to LEO at full payload capacity and a kick stage to the target orbit, in this case GEO. The total cost, $C_l + C_{ks,GEO}$, is then divided by the total mass delivered to GEO by the kick stage, consistent with $m_{s/c,wet}$ from Eq. (1), (3) and (4) but with $\Delta V_{LEO\rightarrow escape}$ scaled to $\Delta V_{LEO\rightarrow GEO}$.

The cost for the kick stage, C_{ks}, is calculated as follows:

$$C_{ks} = (C_{dev} + C_{man}) m_{ks} + C_{prop} m_{ks,prop} \quad (18)$$

where m_{ks} and $m_{ks,prop}$ are calculated according to Eqs. (3)-(4), using $\Delta V_{LEO \to escape}$ for $C_{ks,escape}$ and $\Delta V_{LEO \to GEO}$ for $C_{ks,GEO}$.

Table 1. Cost Elements for NPV Calculation.

Cost element	Value (FY2020[*] $)
C_{dev}	37.19 /kg
C_{man}	1007.1 /kg
C_{op}	6.98×10^6 /year
C_{prop}	0.95 /kg
C_l	free parameter
$C_{ks,escape}$	$f(m_{LEO})$
p	$f(m_{LEO}, C_l)$ /kg

Trajectory optimisation

To optimise the trajectory for maximum NPV, the default genetic algorithm available in MATLAB® is employed. Using the genetic algorithm, the phasing of the Lambert arcs is determined, as well as λ_{MPE}, which determines the relative weight distribution of m_{cargo} and m_{MPE}. The decision vector for the genetic algorithm therefore contains:

1. Duration of the outbound transfer, Δt^O;
2. Stay time at the asteroid, Δt_{stay};
3. Duration of the inbound transfer, Δt^I;
4. Departure date for the outbound transfer, t^O_{dep};
5. Mass fraction for MPE, λ_{MPE}.

The departure and arrival dates, in combination with the orbital elements of the targeted asteroid result in a Cartesian state vector for the asteroid, which is used to find the Lambert arcs. The Lambert solver used in this paper is coded by Izzo in Python,[26] but translated to MATLAB® to be used in conjunction with the built-in genetic algorithm functions in MATLAB®. From the Lambert arcs, the ΔVs associated with the various orbit transfers can be found. By changing the phasing of these transfers, the ΔVs can then be optimised. In order to increase the likelihood of locating a global optimum, the genetic algorithm is run 25 times, initialised with a different seed for each run. The genetic algorithm uses a population of 200 individuals, a uniformly distributed random initial population, and all remaining default options for the setup of the algorithm.

Bounds on the parameters of the decision vector are provided in Table 2. In addition, non-linear constraints are enforced to ensure that the resource mass to sell at Earth is positive (i.e., $m^I_{prop} < m_r$) and that the structural coefficient fulfils during all phases of the transfers, i.e. $\frac{\text{dry mass}}{\text{wet mass}} \geq \epsilon_{min}$.

Table 2. Bounds on Decision Vector Parameters.

Parameter	Minimum	Maximum
Δt^O	2 months	2 years
Δt_{stay}	3 weeks	2 years
Δt^I	2 months	2 years
t^O_{dep}	Jan 1, 2025	Dec 31, 2054
λ_{MPE}	0	1

Target selection

The asteroids targeted in this paper are taken from the JPL Small-Body Database Search Engine.[†] The range of orbital elements for suitable asteroids can be found in Reference [6]. This includes a margin to ensure that no viable asteroids are dismissed just outside the bounds due to changes in the mission scenario:[6]

- Semi major axis: $0.8 \leq a \leq 1.2$ AU;
- Eccentricity: $0 \leq e \leq 0.15$;
- Inclination: $0 \leq i \leq 4.0°$.

All NEAs within these ranges are considered. As noted earlier, the absolute magnitude of the NEA is also taken into account, since the recoverable volatile mass can be approximated using the absolute magnitude. The subset of NEAs considered in this paper, defined by the above ranges for orbital elements, are observed with absolute magnitudes ranging from 21.7 to 31.1, with a distribution given in Figure 2. An estimate of the available resource mass can be determined using Eq. (11) and is given for a range of absolute magnitudes in Table 3. Note that it is assumed that all the NEAs considered are C-type asteroids.

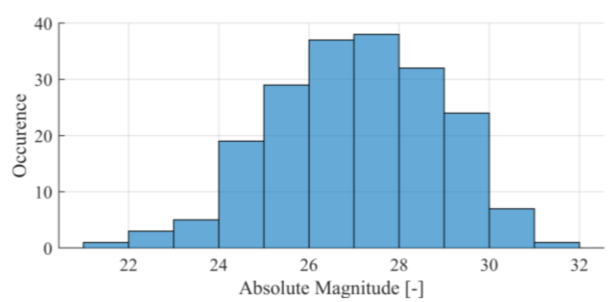

Figure 2. Distribution of Absolute Magnitude of NEA Subset.

[*] Inflated using 2018 NASA New Start Inflation Index, nasa.gov/offices/ocfo/sid/publications, accessed on August 8th, 2019.

[†] ssd.jpl.nasa.gov/sbdb_query.cgi, accessed on August 27th, 2019.

Table 3. Estimated Recoverable Volatile Mass as a Function of Absolute Magnitude.

Absolute Magnitude [-]	$m_{r,available}$ [kg]
22.0	6.859×10^8
23.0	1.723×10^8
24.0	4.328×10^7
25.0	1.087×10^7
26.0	2.730×10^6
27.0	6.859×10^5
28.0	1.723×10^5
29.0	4.328×10^4
30.0	1.087×10^4

CASE STUDIES

To provide specific examples of the mission concept detailed above two case studies are now investigated: the SpaceX BFR and the Arianespace Ariane V ES.

BFR (SpaceX)

From all (super-)heavy-lift launch vehicles currently under development, the SpaceX BFR promises one of the lowest specific launch costs per kg. According to estimates from SpaceX, the BFR will have a payload capacity to LEO of 150 tons (136 metric tonnes) with a launch cost potentially lower than the launch cost of the Falcon 1.[19]. Therefore, using this assumption, the cost of one fully-reusable BFR is estimated at 13.1 M$, the FY2020* cost of a Falcon 1 launch.[21]

Using these parameters and the methodology described above, the genetic algorithm returns the maximum NPV as given in Table 4 for the ten most profitable NEAs during the launch window 2025-2054. For the most profitable mission, to asteroid 2000 SG344, the details for the mission are provided in Table 5.

Ariane V ES

The same analysis has been undertaken for an Ariane V ES launch vehicle, which delivers 21,500 kg to LEO at a cost of 194.89 M$ (FY2020*).[27] While this results in a significantly higher specific cost to LEO than the BFR ($9,065 vs $96), it is still lower than the often quoted $10,000 per kg, used for the economic modelling of other asteroid mining ventures.[4,5,14,18,21] The results of this analysis can be found in Table 6. As can be seen, asteroid 2000 SG344, which was the most profitable target for the BFR mission, still provides for the one of the highest NPVs. The mission details for the most profitable mission to asteroid 2018 AV2 are given in the rightmost column of Table 5. The reasons for the difference in NPV will be discussed later.

Discussion of Case Studies

The difference in profitability of the missions to different target asteroids is due to two elements: first, the orbital elements of the target asteroid (which determines the mission duration and ΔV) and second the absolute magnitude (which determines the maximum recoverable volatile mass). Because of the large payload capacity of the BFR (136 metric tonnes) and the resulting capacity of the cargo spacecraft, the effect of the absolute magnitude is much more important for the BFR case study than for the Ariane V ES case study. This is reflected in Table 4 and Table 6, where the most successful targets for the BFR have in general a lower absolute magnitude than for the Ariane V ES.

For the BFR mission to asteroid 2000 SG344, from Table 5, the maximum absolute magnitude for which $m_{r,available} \geq m_r$ is 27.5. For other missions, the maximum absolute magnitude for which there is no unused capacity on the cargo spacecraft is dependent on the mass budget of the mission (which follows from the ΔVs required to reach the asteroid and GEO), but this value can serve as a guide for a BFR launch.

Table 4. Results for Case Study: BFR

Asteroid	NPV [FY2020 M$]	Absolute Magnitude [-]	Semi major axis [AU]	Eccentricity [-]	Inclination [deg]
2000 SG344	10.9	24.7	0.977	0.067	0.11
2008 EA9	1.28	27.7	1.059	0.080	0.42
2012 TF79	-2.90	27.4	1.050	0.038	1.01
2018 TG6	-4.93	27.1	1.064	0.084	0.71
2015 VC2	-4.95	27.4	1.053	0.074	0.87
2013 BS45	-5.53	25.9	0.992	0.084	0.77
2017 BN93	-7.64	25.4	1.044	0.051	2.12
2018 PM28	-7.91	25.7	1.026	0.075	2.27
2018 PK21	-9.60	25.9	0.988	0.081	1.20
2017 HU49	-9.63	26.5	0.971	0.055	2.27

Table 5. Mission Details for Maximum NPV Missions.

Parameter	BFR	Ariane V ES
Asteroid	2000 SG344	2018 AV2
Departure date	Nov 7th, 2026	Feb 16th, 2047
Duration outbound transfer [days]	296	278
Stay time at asteroid [days]	186	68
Duration inbound transfer [days]	122	143
Total mission duration [days]	605	489
ΔV^O [km/s]	1.258	1.092
ΔV^I [km/s]	0.863	0.591
m_{LEO} [kg]	136,078	21,500
$m_{ks,prop}$ [kg]	71,046	11,225
$m_{ks,dry}$ [kg]	7,894	1,247
m_{cargo} [kg]	41,382	6,313
m_{MPE} [kg]	1,469	719.8
m_{prop}^O [kg]	14,284	1,994
m_{prop}^I [kg]	159,890	21,915
m_r [kg]	372,442	56,822
$m_{r,GEO}$ [kg]	212,551	34,905
Launch cost [M$]	13.1	194.9
Kick stage cost [M$]	8.32	1.31
Development cost [M$] (cargo + MPE)	1.59	0.261
Manufacturing cost [M$] (cargo + MPE)	41.2	7.09
Propellant cost [M$] (cargo)	13.5	1.89
Operations cost [M$]	11.5	9.34
Total cost [M$]	77.7	212.9
Revenue [M$]	103.7	937.1
NPV [M$]	10.9	612.0

The most obvious difference between the two case studies is the profitability. For the BFR case study only 2 asteroids are found to be profitable under the assumptions used, whereas 143 (out of 196) targets for the Ariane V ES case study are profitable. This large difference is mainly due to the difference in the competitive market price (Eq. (17)) in GEO, p, which is much higher when using an Ariane V ES ($26,848) than when using the BFR ($488). This difference in market price is due to the increased specific launch cost, which is much higher for the Ariane V ES due to its smaller payload capacity and higher launch cost. If only Ariane V ES is available it will be more expensive to launch resources directly from Earth to GEO and hence asteroid resources will be more competitive. Therefore, because of the difference in market price, the revenue generated in the Ariane V ES scenario is much larger.

To check whether the bounds on the orbital elements for the initial target selection were unnecessarily constraining, all asteroids are ranked based on the NPV obtained for the Ariane V ES case study (where there is less bias towards the absolute magnitude). The 100 (out of 196) best targets show that the semi-major axis is between 0.93 and 1.10, the eccentricity up to 0.127 and the inclination up to 3.0°, and it can therefore be concluded that the applied range of orbital elements is suitable for the initial pruning of NEAs.

LAUNCHER SELECTION

This section investigates the influence of changing the payload capacity and launch vehicle cost on the profitability of the BFR mission as investigated in the previous section. The reason for choosing the BFR mission scenario over the Ariane V scenario is that the cost reductions for the BFR are more likely in a mid-to far-term time frame.

Figure 3 shows the influence of changing launch cost on the NPV. Note that changing launch cost does not only influence the total cost of the mission, but also the market price in GEO, which is calculated according to Eq. (17). Similarly, Figure 4 shows the influence of changing the payload capacity on the NPV. A linear equation has been fitted to the resulting data, for which the coefficients are given in Table 7. In addition, Figure 5 shows the combined effect of changing the launch cost and payload capacity on the total mission cost, discounted revenue and NPV.

Table 6. Results for Case Study: Ariane V ES.

Asteroid	NPV [FY2020 M$]	Absolute Magnitude [-]	Semi major axis [AU]	Eccentricity [-]	Inclination [deg]
2018 AV2	612.0	28.7	1.030	0.030	0.11
2000 SG344	599.7	24.7	0.977	0.067	0.11
2011 UD21	482.2	28.5	0.979	0.030	1.06
2010 VQ98	474.0	28.2	1.023	0.027	1.48
1991 VG	438.0	28.3	1.032	0.053	1.43
2008 EA9	433.9	27.7	1.059	0.080	0.42
2010 UE51	398.2	28.3	1.055	0.060	0.62
2018 PU23	396.8	28.1	0.964	0.084	0.83
2007 UN12	383.3	28.7	1.054	0.060	0.24
2013 BS45	370.7	25.9	0.992	0.084	0.77

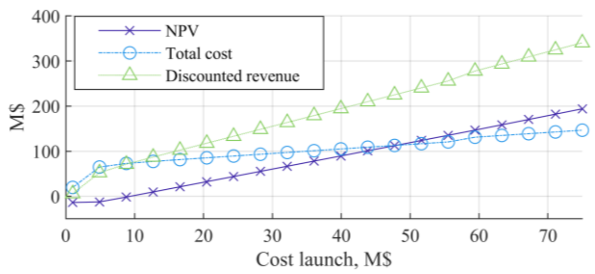

Figure 3. Influence of Launch Cost on Mission Profitability.

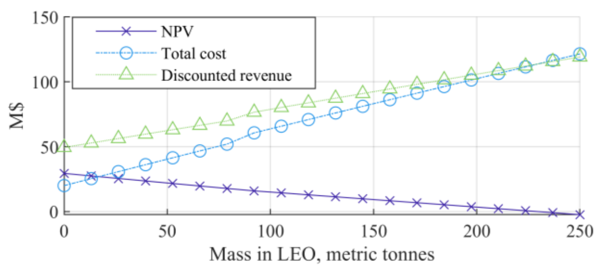

Figure 4. Influence of Payload Capacity on Mission Profitability.

Table 7. Linear Fit to NPV Data.

Dependent variable	Equation
Launch cost	$NPV[\$] = 3.139c_l[\$] - 3.119 \times 10^7$
Payload capacity	$NPV[\$] = -127.4m_{LEO}[\text{kg}] + 2.941 \times 10^7$
Combined	$NPV[\$] = 3.100c_L[\$] - 135.6m_{LEO}[\text{kg}] - 9.899 \times 10^6$

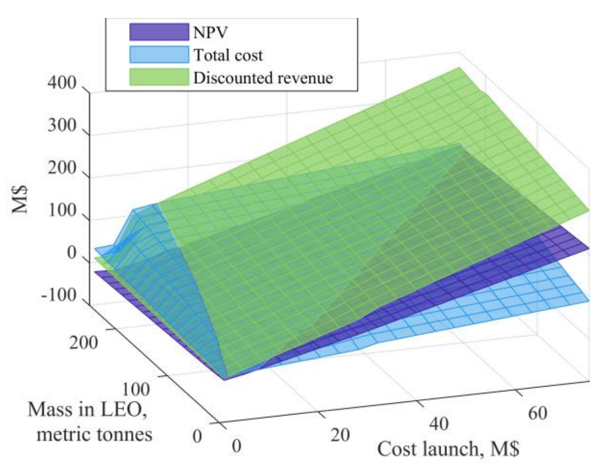

Figure 5. Influence of Launch Cost and Payload Capacity on Mission Profitability.

SENSITIVITY ANALYSIS

Three sensitivity analyses are now provided. First, the effect on profitability of adding another round trip to the mission is investigated. Second, the effect of changing the destination orbit to a hypothetical Lunar Gateway at a collinear Earth-Moon Lagrange point is considered. Finally, a set of Monte Carlo Simulations is performed to investigate the sensitivity of the results to a range of inputs.

Multiple Round Trips

To investigate the effect of multiple round trips, the BFR case study is extended to add a second round trip. The same mission scenario as the single trip is envisioned until delivery to GEO. Then, after a stay time in GEO (Δt_{GEO}), the cargo spacecraft transfers to an escape trajectory for the second round trip. The same mission strategy can then be used; a Lambert arc to the asteroid, proximity operations at the asteroid and then a Lambert arc to return to GEO. However, the asteroid volatile mass that can be produced ($m_{r,mined}$) is now no longer dependent on the stay time at the asteroid during this second trip (Δt_{stay_2}), but on the time since the previous departure from the asteroid, since the MPE is left at the target asteroid. This mission scenario means that the decision vector for the genetic algorithm, with indices to denote the trip where necessary, is extended to:

1. Departure date for the outbound transfer, t_{dep}^O;
2. Duration of the outbound transfer, Δt_1^O;
3. Stay time at the asteroid, Δt_{stay_1};
4. Duration of the inbound transfer, Δt_1^I;
5. Stay time in GEO, Δt_{GEO};
6. Duration of the outbound transfer, Δt_2^O;
7. Stay time at the asteroid, Δt_{stay_2};
8. Duration of the inbound transfer, Δt_2^I;
9. Mass fraction of the MPE, λ_{MPE}.

For this mission, the NPV is calculated as follows:

$$NPV = \frac{pm_{r,GEO_1} - C_{op_2}}{(1+I)^{t_{mis_1}}} + \frac{pm_{r,GEO_2}}{(1+I)^{(t_{mis_1}+t_{mis_2})}} - (C_{dev} + C_{man})m_{s/c,dry} - C_{prop}\, m_{prop}^O - C_{ks,escape} - C_l - C_{op}t_{mis_1} \tag{19}$$

where

$$m_{r,GEO_1} = m_{r_1} - m_{prop_1}^I - m_{prop_2}^O \tag{20a}$$

$$m_{r,GEO_2} = m_{r_2} - m^I_{prop_2} \quad (21b)$$

$$t_{mis_1} = \Delta t^O_1 + \Delta t_{stay_1} + \Delta t^I_2 + \Delta t_{GEO} \quad (22c)$$

$$t_{mis_2} = \Delta t^O_2 + \Delta t_{stay_2} + \Delta t^I_2 \quad (23d)$$

In this analysis, several assumptions are made. First, all propellant required for the second outbound transfer (from GEO to the asteroid) is taken from the propellant that would otherwise be delivered to GEO. Second, the discount for the second trip is based on the *total* mission duration calculated from the start of the first trip. Last, the operation costs for the second trip are only paid at the start of the second trip.

This methodology has been applied to asteroid 2000 SG344, and the results can be found in Table 8. Note that the values presented for ΔV^I_1, ΔV^O_2, and ΔV^I_2 do not include $\Delta V_{GEO \to escape}$.

Table 8. Numerical Results for Multi-Trip Scenario.

Parameter	Value
Departure date 1st trip	Nov 3rd, 2026
t_{mis_1} [days]	633.7
t_{mis_2} [days]	596.4
ΔV^O_1 [km/s]	1.241
ΔV^I_1 [km/s]	0.857
ΔV^O_2 [km/s]	1.134
ΔV^I_2 [km/s]	1.027
m_{r,GEO_1} [kg]	100,056
m_{r,GEO_2} [kg]	203,871
Revenue 1st trip [M$]	48.8
Revenue 2nd trip [M$]	99.5
Total cost at departure [M$]	78.5
C_{op_2} [M$]	11.4
NPV [M$]	25.4

Lunar Gateway

To model a mission that sells LOX/LH2 at the Lunar Gateway, both the propellant required for the inbound transfer (m^I_{prop}) and the market price (p) are modified. The location of the Lunar Gateway, at a halo orbit in the Earth-Moon system, is approximated energetically as being in a circular orbit at Moon-distance from the Earth. This means that to calculate m^I_{prop} in Eq. (13a), $\Delta V_{escape \to GEO}$ is replaced with $\Delta V_{escape \to Moon}$. Moreover, to calculate the market price, the cost for the kick-stage to the Lunar Gateway has to incorporate an updated propellant requirement: $\Delta V_{LEO \to GEO}$ is modified to $\Delta V_{LEO \to Moon}$.

Table 9 shows the optimised results obtained using this updated mission scenario for a BFR mission to asteroid 2000 SG344 and the Lunar Gateway. The remaining optimised mission details are as shown in Table 5, within 1 day difference of phasing, which is considered within the tolerances of the genetic algorithm.

Table 9. BFR Mission from Asteroid 2000 SG344 to Lunar Gateway.

Parameter	GEO (from Table 5)	Lunar Gateway
ΔV kick stage LEO to orbit (to determine p) [km/s]	3.940	3.968
ΔV^I_{tot} cargo spacecraft [km/s]	2.136	1.286
m^I_{prop} [kg]	159,890	105,756
$m_{r,GEO}$ [kg]	212,551	267.911
p [$/kg]	488	493
Revenue [M$]	103.7	132.1
NPV [M$]	10.9	34.8

Monte Carlo Simulations

In order to investigate the influence of key parameters used in the optimisation, a range of Monte Carlo simulations is performed. Uncertainties on the input parameters are considered, after which the uncertainty of the resulting NPV can be determined. Table 10 shows a range of input parameters which have an influence on the resulting NPV and the parameters used to model the uncertainty as a normal probability density function. The standard deviation used is arbitrarily chosen as 10% of the mean value. However, this should result in a relative metric for the sensitivity of each parameter with respect to the others.

Table 10. Inputs for Monte Carlo Simulation of BFR Case Study.

Parameter	Mean value	Standard deviation
Throughput rate, r	200 kg/day/kg$_{MPE}$	20 kg/day/kg$_{MPE}$
Discount rate, I	10 %	1 %
Manufacturing cost, C_{man}	1007.1 /kg	100.7 /kg
Development cost, C_{dev}	37.19 /kg	3.72 /kg
Operation cost, C_{op}	6.98×10^6	6.98×10^5
Minimum structural coefficient, ϵ_{min}	0.10	0.01
Albedo, p_{v_c}	0.06	0.006
Density, ρ_c	1300 kg/m^3	130 kg/m^3
Recovery ratio, $\lambda_{volatile}$	0.10	0.01

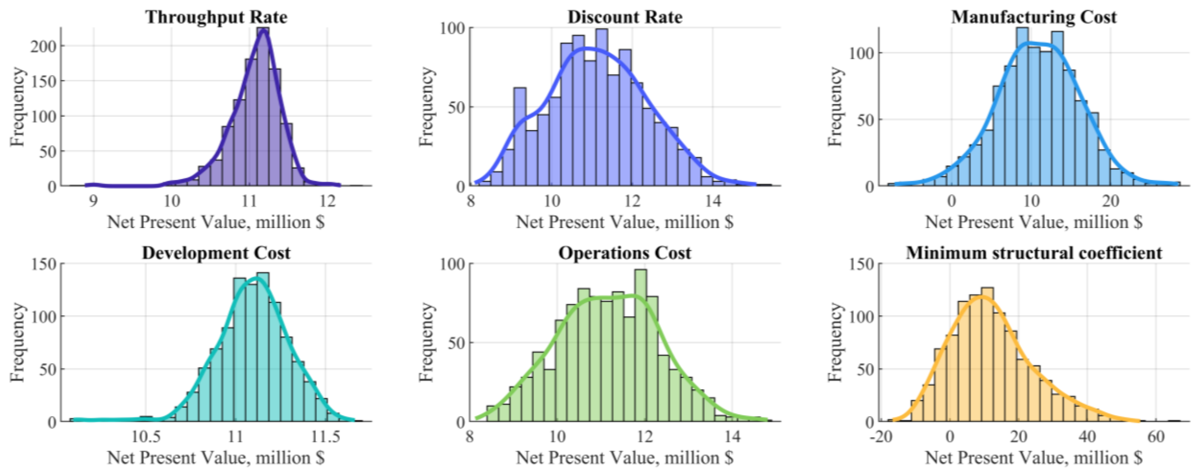

Figure 6. Result of Monte Carlo Analysis: Asteroid 2000 SG344.

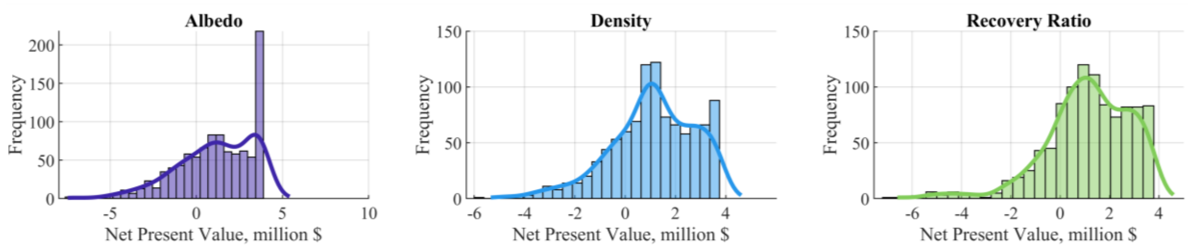

Figure 7. Result of Monte Carlo Analysis: Asteroid 2018 EA9.

The simulations are performed for the BFR case study using asteroid 2000 SG344 for all parameters except p_{v_c}, ρ_c, and $\lambda_{volatile}$. These parameters influence $m_{r,available}$ and since this is much larger than $m_{r,mined}$ for asteroid 2000 SG344, the effect on the NPV would not be apparent. Therefore, the mission to asteroid 2018 EA9 is investigated for these three input parameters, for which $m_{r,available} = m_{r,mined}$ in the BFR mission optimised for maximum NPV.

For each simulation, 1000 scenarios are optimised and the resulting NPV is displayed using a histogram and kernel probability density function in Figure 6 and Figure 7. From Figure 6 and Figure 7 the relative influence of certain parameters on the final NPV can be seen, based on the assumed probability density functions of the input parameters. It can then be deduced that one of the most influential parameters is the minimum structural coefficient. This has to be taken into account in the determination of $m_{r,transportable}$ and therefore limits m_r, as well as while calculating the kick stage dry mass (which dictates the remaining mass for the cargo spacecraft). What stands out in Figure 7 is that no NPV above 3.71 M$ is found, because at that point the cargo spacecraft is at full capacity. For all other simulations, the cargo spacecraft still has unused storage capacity left. In addition, Figure 7 shows that a change in albedo has a relatively larger effect on $m_{r,available}$ than the same change (in percentage) of density and recovery ratio.

CONCLUSION

In this paper, an investigation of the influence of launch vehicle payload capacity and cost on the profitability of an asteroid mining mission is presented. The analysis combines economic modelling and trajectory optimisation in order to investigate a representative mission scenario. This mission scenario includes a launch vehicle used at full payload capacity, containing a cargo spacecraft and mining and processing equipment to process asteroid material into water and then LOX/LH2. Upon delivery of the mined resources to GEO, the Net Present Value (NPV) is calculated to represent the profitability of the mission, which includes the time-cost of money.

Results show that for decreasing launch costs, the NPV that can be achieved also decreases. This is because the decrease in total cost is more than offset by the decrease in revenue. The revenue is dependent on the launch cost because the resources are sold at a price competitive with launching them from Earth. The market price therefore decreases if the specific launch cost (per kg) decrease. Similarly, the results show that for increasing payload capacity, the NPV decreases as well. This can be explained by the decreasing specific costs (per kg) for launching resources from Earth, which decreases the market price in GEO. Case studies for the SpaceX BFR (136 metric tonnes for M$13.1) and the Arianespace Ariane V ES (21.5 metric tonnes for M$195) show that for asteroid 2000 SG344, the NPV is M$11 and M$599, respectively. It can be concluded that the specific launch cost has a significant impact on the profitability of asteroid mining missions. However, it should be noted that in the calculation of the market price, it is assumed that the launch vehicle under consideration is the only launch vehicle that can be used for delivering resources to GEO. Nonetheless, the quantitative results are still valid: when launch vehicles become bigger and/or cheaper, asteroid mining missions are less profitable.

Extending the investigated mission scenario for the BFR case study with a second trip shows that a higher NPV can be generated (M$25.4), although a considerable portion of the returned resources have to be used for the next outbound transfer, and can thus no longer be sold in GEO. Also, it is shown that by selling the resources at the Lunar Gateway instead of GEO, which changes the inbound ΔV and the market price, a higher NPV can be generated (M$34.8).

ACKNOWLEDGEMENTS

Merel Vergaaij gratefully acknowledges the College of Science and Engineering at the University of Glasgow for supporting this work. Colin McInnes was supported by a Royal Society Wolfson Research Merit Award and a Royal Academy of Engineering Chair in Emerging Technologies.

REFERENCES

[1] Andrews, D. G., Bonner, K. D., Butterworth, A. W., Calvert, H. R., Dagang, B. R. H., Dimond, K. J., Eckenroth, L. G., Erickson, J. M., Gilbertson, B. A., Gompertz, N. R., Igbinosun, O. J., Ip, T. J., Khan, B. H., Marquez, S. L., Neilson, N. M., Parker, C. O., Ransom, E. H., Reeve, B. W., Robinson, T. L., Rogers, M., Schuh, P. M., Tom, C. J., Wall, S. E., Watanabe, N., and Yoo, C. J. "Defining a Successful Commercial Asteroid Mining Program." *Acta Astronautica*, Vol. 108, 2015, pp. 106–118. doi:10.1016/j.actaastro.2014.10.034.

[2] Lewis, J. S. *Mining the Sky*. Addison-Wesley Publishing Company, Inc., 1996.

[3] Sonter, M. J. "The Technical and Economic Feasibility of Mining the Near-Earth Asteroids." *Acta Astronautica*, Vol. 41, No. 4–10, 1997, pp. 637–647. doi:10.1016/S0094-5765(98)00087-3.

[4] Gerlach, C. L. Profitably Exploiting Near-Earth Object Resources. 2005.

[5] Ross, S. D. *Near-Earth Asteroid Mining*. Control and Dynamical Systems, Caltech 107-81, Pasadena, CA 91125, 2001.

[6] Vergaaij, M., McInnes, C., and Ceriotti, M. Economic Assessment of High-Thrust and Solar-Sail Propulsion for Near-Earth Asteroid Mining. Presented at the 5th International Symposium on Solar Sailing, Aachen, Germany, 2019.

[7] Bus, S., and Binzel, R. P. *Small Main-Belt Asteroid Spectroscopic Survey, Phase II*. Planetary Science Institute, 2003.

[8] Dorrington, S., and Olsen, J. Logistics Problems in the Design of an Asteroid Mining Industry. 2018.

[9] Sanchez, J. P., and McInnes, C. "Asteroid Resource Map for Near-Earth Space." *Journal of Spacecraft and Rockets*, Vol. 48, No. 1, 2011, pp. 153–165. doi:10.2514/1.49851.

[10] Yárnoz, D. G., Sánchez, J.-P., and McInnes, C. "Easily Retrievable Objects among the NEO Population." *Celestial Mechanics and Dynamical Astronomy*, Vol. 116, No. 4, 2013, pp. 367–388. doi:10.1007/s10569-013-9495-6.

[11] Tan, M., McInnes, C., and Ceriotti, M. "Low-Energy near Earth Asteroid Capture Using Earth Flybys and Aerobraking." *Advances in Space Research*, Vol. 61, No. 8, 2018, pp. 2099–2115. doi:10.1016/j.asr.2018.01.027.

[12] Mingotti, G., Topputo, F., and Bernelli-Zazzera, F. "Earth–Mars Transfers with Ballistic Escape and Low-Thrust Capture." *Celestial Mechanics Dynamical Astronomy*, Vol. 110, No. 2, 2011, pp. 169–188. doi:10.1007/s10569-011-9343-5.

[13] Gargioni, G., Alexandre, D., Peterson, M., and Schroeder, K. Multiple Asteroid Retrieval Mission from Lunar Orbital Platform-Gateway Using Reusable Spacecrafts. 2019.

[14] Sonter, M.J. *The Technical and Economic Feasibility of Mining the Near-Earth Asteroids*.

MSc (Hons). University of Wollongong, Department of Physics and Department of Civil and Mining Engineering, Wollongong, 1997.

[15] Erickson, K. Optimal Architecture for an Asteroid Mining Mission: Equipment Details and Integration. Presented at the Space 2006, San Jose, California, 2006.

[16] Just, G. H., Smith, K., Joy, K. H., and Roy, M. J. "Parametric Review of Existing Regolith Excavation Techniques for Lunar In Situ Resource Utilisation (ISRU) and Recommendations for Future Excavation Experiments." *Planetary and Space Science*, 2019, p. 104746. doi:10.1016/j.pss.2019.104746.

[17] Gertsch, R., and Gertsch, L. "Economic Analysis Tools for Mineral Projects in Space." *Space Resources Roundtable*, 2005.

[18] Hein, A. M., Matheson, R., and Fries, D. A Techno-Economic Analysis of Asteroid Mining. 2018.

[19] Musk, E. "Making Life Multi-Planetary." *New Space*, Vol. 6, No. 1, 2018, pp. 2–11. doi:10.1089/space.2018.29013.

[20] Battin, R. H. *An Introduction to the Mathematics and Methods of Astrodynamics, Revised Edition*. American Institute of Aeronautics & Astronautics, Reston, VA, 1999.

[21] Wertz, J. R., Everett, D. F., and Puschell, J. J. *Space Mission Engineering: The New SMAD*. Microcosm Press, Hawthorne, CA, 2011.

[22] Beauchamp, P. M., Cutts, C., James. A., Surampudi, R., Blosiu, J., Stella, P., Elliott, J., Castillo, J., Yi, T., Lyons, J., Piszczor, M., McNatt, J., Taylor, C., Gaddy, E., Liu, S., Plichta, E., and Iannello, C. Solar Power Technologies for Future Planetary Science Missions.

[23] Lide, D. R., Ed. *CRC Handbook of Chemistry and Physics*. CRC Press, Boca Raton, Florida, 2018.

[24] Chesley, S. R., Chodas, P. W., Milani, A., Valsecchi, G. B., and Yeomans, D. K. "Quantifying the Risk Posed by Potential Earth Impacts." *Icarus*, Vol. 159, No. 2, 2002, pp. 423–432. doi:doi.org/10.1006/icar.2002.6910.

[25] Sutton, G. P., and Biblarz, O. *Rocket Propulsion Elements*. John Wiley & Sons, 2010.

[26] Izzo, D. "Revisiting Lambert's Problem." *Celestial Mechanics and Dynamical Astronomy*, Vol. 121, No. 1, 2015, pp. 1–15. doi:10.1007/s10569-014-9587-y.

[27] Boone, T. R., and Miller, D. P. "Capability and Cost-Effectiveness of Launch Vehicles." *New Space*, Vol. 4, No. 3, 2016, pp. 168–189. doi:10.1089/space.2016.0011.