WHEN THE PRICE IS RIGHT: STOCHASTIC MODELING OF AN ASTEROID MINING BUSINESS CASE.

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Introduction: The natural resources contained within Near-Earth asteroids could "sustain a human population of 100 billion until the Sun dies"[1]. However, to date, less than 100 g of material has ever been extracted from an asteroid. The largest extraction of ~60 g achieved by Osiris-Rex cost \$1.16 billion, which comes to \$19.3 billion per kg [2]. With launch costs to GTO at a conservative \$20,000 per kg, the current cost to extract materials from asteroids is almost 1,000,000 times more expensive than launching materials from Earth [3]. This is an extreme economic gap to close.

Deep Space Industries (DSI) and Planetary Resources (PR) are two companies that attempted to close this gap. However, both went bankrupt before launching a satellite outside of Earth's orbit. Now in 2023, companies such as Karman+, AstroForge, and TransAstra are looking to achieve what DSI and PR could not.

To understand the economics that face these asteroid mining companies, we built two stochastic, mathematical models. The models make the specific assumption that water was extracted from an asteroid and sold at EML1 but can be easily adapted to address different asteroid mining business cases.

The Spacecraft Cost for Asteroid Mining Model (SCAMM) estimates the mass, R&D cost, theoretical first unit (TFU) cost, and the mass of water delivered to EML1, among numerous other spacecraft specific parameters. The Asteroid Mining Cash Flow model (AMCF) uses the outputs from SCAMM, among other stochastic inputs, to determine the cost per kg, NPV and IRR of the theoretical asteroid mining business.

The median cost to deliver a kg of water to EML1 from an asteroid in 2038, from 50,000 Monte Carlo runs of AMCF, was \$3,500 per kg. The cost per kg from a single simulation is shown in Figure 1. The \$3,500 per kg is a substantial cost decrease compared to Osiris-Rex, and it has a comparative cost advantage to current launch costs.

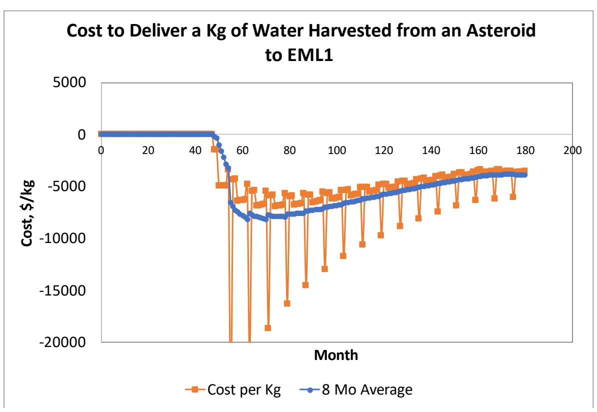

Figure 1: A single simulation value of the cost per kg to bring water from an asteroid to EML1.

However, a comparative cost advantage does not necessarily mean that a company is profitable. It was our assumption that launch cost per kg was equivalent to the sale price per kilogram, as launch from Earth is a competitive supply source to an asteroid mining company. This means that the profit margin on selling asteroid water after 15 years is the only ~10%. Using launch costs as sale price yielded a median NPV, from 50,000 Monte Carlo runs of AMCF, of -\$3.4 billion.

The most influential variables on NPV are the rate at which a company can launch mining spacecraft, the sale price of water at EML1, OPEX, and the roundtrip time to the asteroid. While technical in nature, these variables are more linked to the business side of scaling a company rather than the technical engineering challenges commonly associated with asteroid mining.

Spacecraft Cost: Our engineering technical challenge was to design a spacecraft that could extract and process 1,000 kg of water from an asteroid. This was a 15,000x scale up from the extraction capabilities of Osiris-Rex.

The mass of the excavation system was estimated in SCAMM by calculating the volume needed to contain 1,000 kg of water from asteroid material in a single, or multiple, scoops. The asteroid was assumed to be a rubble pile. A material density, mass factor, SMAD Cost Estimation Relationship (CER), and other factors were then applied to come to a final excavation system mass and cost [4].

A similar method was used to calculate the mass and cost of the processing subsystem, power system, and all other spacecraft subsystems. Iterative calculations were then performed to calculate the amount of propellant needed to go from EML1 to an asteroid with no harvested water, to go from the asteroid to EML1 with 1,000 kg of water, and then back to an asteroid.

Some key takeaways with regards to spacecraft design were that:

1. Using harvested water from the asteroid as propellant for the return journey had high cost and mass savings.
2. Solar thermal concentrators as a heat source to react the asteroid material had significantly better mass and cost than using solar panels.
3. Increasing the processing time at the asteroid allowed for a significantly lower dry mass.

The metric of recovery sale price is used to evaluate different scenarios in the SCAMM model. Recover sales price, in thousands of dollars per kg, is the price that the water would need to be sold at to recover the R&D, TFU, and launch costs of a spacecraft. This cost does not include OPEX and economies of scale which are applied in the AMCF model.

The recovery sale price was $31,000/kg for a single LH2/LO2 powered craft making 10 round trips to an asteroid. The most influential factors that go into the recovery sale price are shown in Figure 2. The economies of scale introduced by the AMCF model are able to reduce this cost 10 fold even with the added Opex costs.

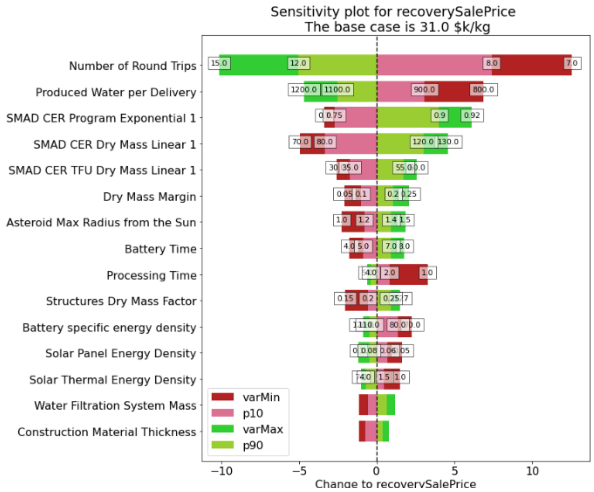

Figure 2: Sensitivity plot showing the most influential variables on recovery sale price.

Business Economics: The AMCF model considered distribution ranges for 22 input parameters that were taken from the SCAMM model and literature. The inputs cover CAPEX related factors, such as Research and Development time and cost, Manufacturing cost and economics of scale, and launch cost. It also considers operations growth parameters, such as number and frequency of craft launched, OPEX per craft, OPEX economics of scale, and fixed price and quantity contract options. Each input parameter was modeled with a distribution function and correlated to each of the other inputs. For example, a higher starting launch cost correlated to a higher launch cost decline rate and vise versa. These inputs were then fed into the dynamic and stochastic AMCF model that yielded ranges of economic metrics, such as NPV and payout time.

For the full range of inputs tested across the 50,000 simulations, only 2.1% of the results yielded a positive NPV. The full range of outputs span from $-14B to $+4B, with a median value of $-3.4B. The most significant inputs for generating a higher NPV are shown in the tornado plot in Figure 3. The top several inputs are all related to the ability to scale the business quickly and efficiently, while bringing back as much water per trip as quickly as possible. CAPEX related inputs seemingly have very little effect on the overall business case. With a discount rate of 15%, the business' ability to recover the upfront and reoccurring costs as quickly as possible through revenue generation, given the time value of money, is the primary driver for success.

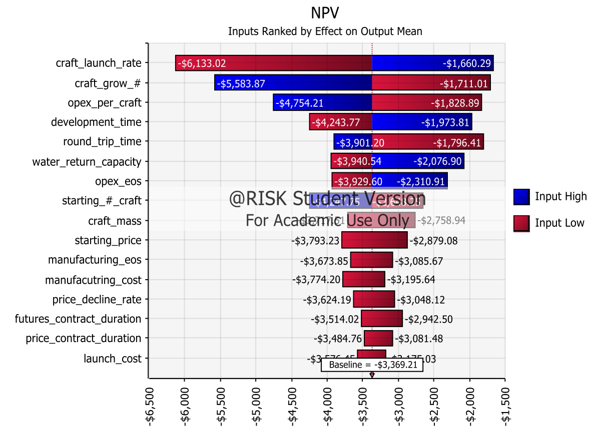

Figure 3: Sensitivity Plot showing the most influential variables on NPV.

Although, these results paint a seemingly dim picture, the insights and utility of these models are in determining the threshold values to make a successful business. Changing just the operations growth and efficiency parameters to P10 input values yields positive NPVs for 28.8% of the results.

Future considerations for the AMCF model entail shared risk and cost methods for business such as Public-Private-Partnerships. Additionally, the inclusion of other commodities from the asteroid in the sale may make the economics more favorable.

References:

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[2] https://www.planetary.org/space-policy/cost-of-osiris-rex
[3] https://en.wikipedia.org/wiki/Falcon_Heavy
[4] Wertz, J. (2022). Space Mission Engineering- The New Smad

Additional Information: If you have any questions or need more information regarding the abstract, please contact Matthew Rehberg (mrehberg@blueorigin.com) or Joseph Kenrick (joseph@lunaroutpost.com).