The Space Superhighway: A Cost Analysis of an In-Space Logistics Resupply Network

Paul D. Friz[*] and Daniel J. Tiffin[†]
NASA Langley Research Center, Hampton, VA, 23681, USA

Edward W. Rosenthal[‡]
Georgia Institute of Technology, Atlanta, GA, 30332

The Space Superhighway is a concept for an in-space logistics network for payload delivery and propellant resupply within the Earth-Moon system. It is expected that in the next several years the number of spacecraft in cislunar space will increase significantly. Commercial launch service providers have significantly reduced the cost of access to space and reduced the barrier to entry for private companies to build and operate their own satellites. Many of these newer satellites are being designed to take advantage of future In-space Servicing, Assembly, and Manufacturing (ISAM) capabilities. In addition, the National Aeronautics and Space Administration (NASA) intends to develop and maintain a sustained human presence in cislunar space and on the surface of the Moon. The sustained lunar presence will then serve as a steppingstone for human missions to Mars. The combined demand for propellant resupply and payload delivery in cislunar space for NASA's Moon to Mars campaign in addition to commercial ventures will likely exceed 1,000 t in the upcoming decades. This work presents a concept for an in-space logistics network to fulfill that demand. The network consists of commercial launch vehicles, propellant tankers, orbital depots, and in-space electric propulsion tugs. This work specifically analyzes the cost of developing, producing, and operating such a network at varying levels of customer demand.

Nomenclature

CBE = Current Best Estimate
CDF = Cumulative Distribution Function
C&DH = Command & Data Handling
CER = Cost Estimating Relationship
CH_4 = Methane
ConOps = Concept of Operations
ΔV = Change in Velocity
EO = Extremely Optimistic
EXAMINE = Exploration Architecture Model for the IN-space and Earth-to-orbit modeling
GEO = Geosynchronous Equatorial Orbit
GN&C = Guidance, Navigation, & Control
H_2 = Molecular Hydrogen
ISAM = In-space Servicing, Assembly, and Manufacturing
Kr = Krypton
LEO = Low Earth Orbit
LOX = Liquid Oxygen
LV = Launch Vehicle
MEL = Master Equipment List
MGA = Mass Growth Allowance
MOCET = Mission Operations Cost Estimation Tool

---

[*] Aerospace Engineer, Systems Analysis and Concepts Directorate
[†] Aerospace Engineer, Systems Analysis and Concepts Directorate, Member AIAA
[‡] Student Engineer, Systems Analysis and Concepts Directorate

PCEC = Project Cost Estimating Capability
PDF = Probability Distribution Function
REDSTAR = REsource Data STorage And Retrieval
RP-1 = Rocket Propellant-1
NAFCOM = NASA/Air Force Cost Model
NRHO = Near Rectilinear Halo Orbit
ONCE = One NASA Cost Engineering
SEER-H = System Estimation and Evaluation of Resources-Hardware
t = Metric Ton (1000 kg)
SEP = Solar Electric Propulsion
SA = State-of-the-Art
Xe = Xenon

I. Introduction

IN-SPACE Servicing Assembly and Manufacturing (ISAM) has long been touted as a capability that will dramatically decrease the cost of space exploration[1–3] There is currently significant research in the areas of orbital refueling[4], in-space and lunar surface assembly[5, 6], robotic arms[7, 8], and in-space manufacturing[9]. Many of these ISAM capabilities require numerous unconventional and or small payloads to be delivered to a variety of locations throughout cislunar space. While there is significant research into ISAM technologies, they are not being actively considered for current missions because of the unknown cost of delivering small payloads throughout the Earth-Moon system. This work presents a conceptual in-space delivery network capable of delivering a wide range of payloads throughout cislunar space. The network consists of commercial expendable and or fully reusable Launch Vehicles (LVs), in-space propellant tankers, in-space propellant and logistics depots, as well as in-space propulsion tugs.

A graphic showing the key elements of the Space Superhighway is displayed in Fig. 1. Launch vehicles deliver propellant and logistics payloads to Low Earth Orbit (LEO). These payloads can either enter their own orbit or rendezvous with a LEO depot. An in-space transportation vehicle will then rendezvous with the LEO depot or the freely orbiting payload, dock with it, and transport it to its final destination. The final destination could be another orbit in LEO,

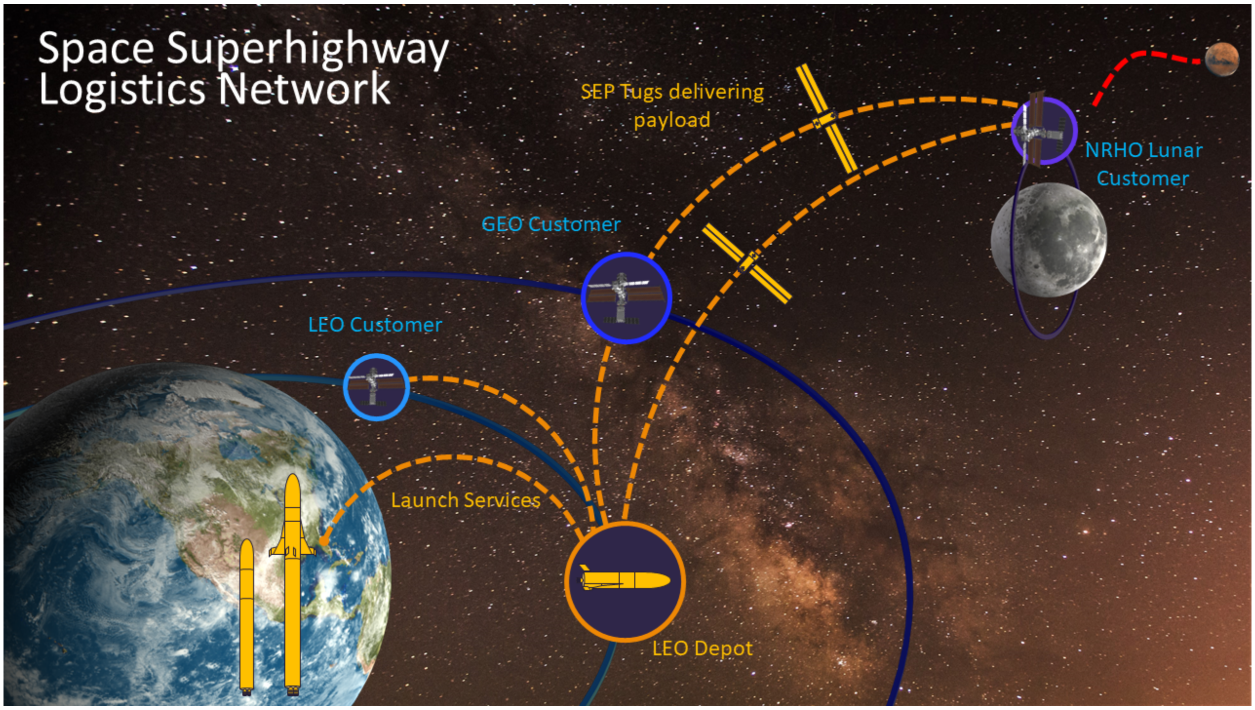


Fig. 1 Space Superhighway high level concept

Geosynchronous Equatorial Orbit (GEO), an orbit about the Moon or anywhere in the Earth-Moon system. However, this work will focus on transfers from LEO to Near Rectilinear Halo Orbit (NRHO) about the Moon, but any destination in cislunar space is theoretically possible.

The Space Superhighway is built off previous work comparing expendable and reusable in-space refueling tankers being delivered to lunar orbit[10]. This work expands on that study by modeling not only the reusable tankers but the launch vehicles and Solar Electric Propulsion (SEP) tugs as well. This paper is the second of two papers presented at AIAA ASCEND 2022. The first paper titled "The Space Superhighway: Building an In-Space Logistics Resupply Network"[11] focuses on the mission and spacecraft design. The present paper's objective is to estimate the cost of developing, producing, and operating this network under varying assumptions of reusability and customer demand. The ultimate goal is to determine in which scenarios reusable or expendable systems are more cost effective.

The next section explores the Concept of Operations (ConOps) for the architecture. Section III provides an overview of the methods used to model the architectures, Sec. IV discusses in detail the cost modeling tools and assumptions, Sec. V will present results, and Sec. VI will provide concluding remarks and future work.

II. Concept of Operations

A "bat chart" showing the ConOps for two competing architectures for the Space Superhighway is shown in Fig. 2. The first architecture utilizes exclusively fully expendable vehicles that will be discarded after each use, whereas the second architecture utilizes a fully reusable approach where every vehicle is reused multiple times.

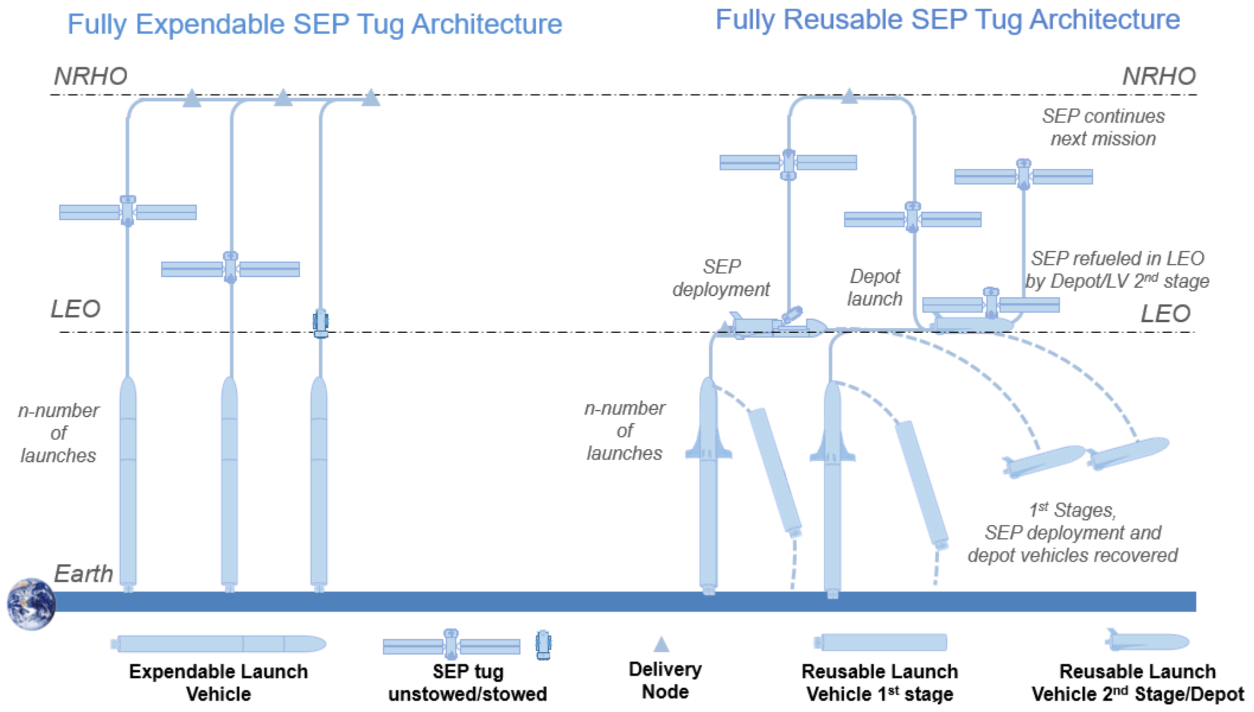


Fig. 2 Fully expendable architecture vs. fully reusable architecture (not to scale)

The fully expendable SEP tug architecture is outlined on the left side of Fig. 2. This architecture is quite simple and traditional. Expendable LVs deliver expendable SEP tugs carrying customer payload to LEO. The SEP tugs then slowly spiral out to NRHO, deliver their payload to the customer, and then are disposed. LVs and SEP tugs are built and launched until the customer demand is satisfied. The payload could be whatever the customer needs, however, the customer will need to supply the payload in a way that it can be transported. The SEP tug comes with a docking adapter, but no payload bay or customer propellant storage.

The fully reusable SEP tug architecture is detailed on the right side of Fig. 2. The SEP tugs in this architecture are identical to the ones used in the fully expendable architecture, however, their payload capacity and therefore gross mass is greatly reduced to allow them to have enough delta-V (ΔV) to deliver their payload to NRHO and make it back to

LEO. The major difference in the fully reusable architecture is the LV. Many propellant options were studied for the reusable LV, but the most cost effective were methane/liquid oxygen (CH_4/LOX) first stage and a hydrogen/liquid oxygen (H_2/LOX) second stage[10]. The first stage boosts the second stage but reserves enough propellant to return to the launch site and land. The second stage carries the SEP tug and its payload to LEO but carries a heat shield, aerosurfaces, and enough propellant to deorbit and land safely back on Earth. The first and second stages are then refurbished and returned to service. Meanwhile the SEP tug spirals out to NRHO, delivers its payload, and spirals back to LEO. The second stage of the reusable LV is launched to LEO to meet the returning SEP tug. This time the second stage acts as a depot and instead of carrying a SEP tug it carries a Xe tank and/or additional customer payload. Depending on the exact nature of the customer payload, the depot may be configured to carry Xe, payload, or both. Thus, there are circumstances where two second stage depots may need to be in LEO at a time, or a SEP tug may have to dock with two second stage depots to retrieve its required propellant and payload. It is assumed that a total of four reusable LV first and second stage combinations are produced to allow two second stages to be in space while two are being refurbished. Once the 2nd stage depot has delivered all its propellant and payload, it returns to Earth, lands, and is refurbished for its next flight.

III. Methodology Overview

This section describes the tools, methods, and assumptions used in this work. The overall methodology is shown by the flow chart in Fig. 3. First the mission and trajectory design are completed to determine the ΔV requirements for each vehicle. The ΔV requirements for the SEP tugs were determined using the Edelbaum method[12, 13]. The ΔV and other outputs from the trajectory design are then used as an input to the tool Exploration Architecture Model for the IN-space and Earth-to-orbit modeling (EXAMINE) which is used to size all vehicles including: LV stages, depots, tankers, and in-space tugs[14]. Often the vehicle sizing determined in EXAMINE will affect the trajectory, and so several iterations between EXAMINE and the trajectory tools will need to be performed for a vehicle design to converge. EXAMINE outputs a Master Equipment List (MEL) that includes a list of all the components of a vehicle along with their masses and quantities. Each MEL produced by EXAMINE is an input to the parametric cost estimating tool System Estimation and Evaluation of Resources-Hardware (SEER-H). SEER-H is used to estimate the cost of the development and production of each vehicle. Since this work analyzes several hundred design variations of each vehicle, a Python script was written to automatically translate the output from EXAMINE into SEER-H command files[15, 16]. While most spacecraft components are more accurately modeled in SEER-H, some can be more accurately modeled using NASA's Project Cost Estimating Capability (PCEC) tool[17]. Output from EXAMINE and the mission/trajectory design is then fed into the Mission Operations Cost Estimation Tool (MOCET) to estimate the cost of in-space operations[18]. Finally, to model the cost of reusing spacecraft, several overarching assumptions were made. All this data is then compiled using a combination of Python, Excel, and MATrix LABoratory (MATLAB) to estimate the total cost of the proposed architectures.

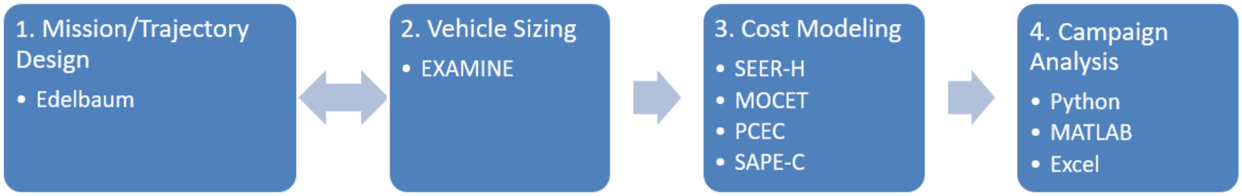


Fig. 3 Flow chart showing processes and tools used in this study

The following subsections provide a detailed description of the tools and major assumptions used in this work. However, this work focuses on cost modeling and campaign analysis. For more details on the mission and trajectory design, and vehicle sizing see "The Space Superhighway: Building an In-Space Logistics Resupply Network"[11].

IV. Cost Modeling Tools and Assumptions

The costs presented in this work are divided into five categories: development and production cost, in-space operations cost, reuse/refurbishment cost, propellant cost, and total cost. The following subsections describe each of these categories in detail as well as the tools or assumptions that were used to model them. All costs presented in this work have been normalized unless otherwise noted. The normalization constant is the development cost of a reusable

SEP tug with a 25 t payload capacity.

Reuse cost is the cost of refurbishing a hardware element after it has flown and preparing it for its next flight. Since the expendable tankers and launch vehicles are used only once, they do not incur a reuse cost. Likewise, as this study isn't considering the ability to service SEP tugs, even though the SEP tugs are reused in the reusable architecture they do not incur a reuse cost. The reusable LV first and second stages are the only elements that incur reuse cost. Propellant cost is the cost of the propellant used by the reusable LVs and the SEP tugs. The cost of Xe and Kr is quite significant with Xe being on the order of thousands of dollars per kg and Kr costing hundreds of dollars per kg. Propellants include Xe, Kr, H_2/LOX, CH_4/LOX, and RP-1/LOX. However, the cost of the chemical propellants, H_2, CH_4, RP-1, and LOX is less than 0.1% of the total cost in nearly all cases. The cost of the chemical propellants is only included/shown if they account for more than 1% of the total cost of an architecture. Operations cost is the cost of labor for the employees remotely operating the spacecraft/launch vehicles and the costs incurred by utilizing in-space communications assets. The total cost is simply the sum of the development, production, reuse, propellant, and operations costs for an element or architecture.

A. Development and Production Cost

Development and production cost are the expenses associated with designing and building a particular vehicle. Development cost includes all costs associated with the design, development, testing, and evaluation of a hardware element, such as a LV stage or SEP tug, including building and testing prototypes. Production cost includes all the costs associated with constructing the hardware elements and preparing them for their initial flight. SEER-H is the primary tool used to model development and production cost, but there are a small number of components where PCEC is more appropriate in the context of this work. For the purposes of this study, individual avionics components such as control boards, processors, transponders, and individual antennas were not modeled. Instead, the mass of the Command & Data Handling (C&DH), Guidance, Navigation, & Control (GN&C), and communications subsystems was estimated in EXAMINE. SEER-H requires information about the function of individual electronics boards and the number of components on them to provide accurate estimates. PCEC can model the cost of the C&DH, GN&C, and communications subsystems using just their masses, so PCEC was used to model the majority of the avionics in this study. The following subsections describe the use and accuracy of SEER-H and PCEC in more detail.

1. SEER-H

SEER-H is a commercial parametric cost estimating tool developed by Galorath Inc.[*] It is one of the standard tools used by NASA to estimate the costs of space missions for early planning or proposal phases. Galorath performed an internal validation study of SEER-H where it was used to predict the costs of 15 NASA space science missions. Galorath found that SEER-H's mean error in predicting mission cost was -1% with a standard deviation of 19%[19]. NASA performed an independent validation study of SEER-H and other parametric cost estimating tools in an attempt to verify Galorath's results[20, 21]. The NASA SEER-H validation study reported that point estimates modeled in SEER-H had an average error of 25%, median error of -0.3%, and a standard deviation of 43%. The analysis of SEER-H's uncertainty quantification capabilities found that 75% of the cases studied fell within SEER-H's 80% confidence interval.[†]

The backbone of SEER-H is its proprietary Cost Estimating Relationships (CERs) and associated database of cost history. To model the cost of a spacecraft in SEER-H, the user inputs "work elements" which correspond to different components of the spacecraft. For each "work element," the user chooses an "application" which sets the majority of the inputs for SEER-H's CERs. SEER-H's database contains hundreds of mechanical/structural "applications" for spacecraft components, examples include: payload adapter, separation mechanism, space propulsion component, aerodynamic control surface, spacecraft antenna dish, spacecraft harness, gimbal mechanism, etc. Mechanical/structural "applications" in SEER-H are modeled using mass, material composition, complexity of form, complexity of fit, construction process, amount of new design, design replication, certification level, and a number of other inputs. Electronic components are modeled using the number of printed circuit boards, number of discrete components per board, number of integrated circuits per board, clock speed, number of pins, percent new design, and a number of other inputs. If the user knows all these inputs, they can potentially improve the accuracy of the estimate by inputting them into SEER-H. Otherwise, SEER-H will estimate the inputs using its database and the electronic "application" input by

---

[*] Reference to or appearance of any specific commercial products, processes, or services by trade name, trademark, manufacturer, or otherwise does not constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or NASA.

[†] SEER-H outputs project costs at probability levels in intervals of 10%. Thus 80% confidence intervals must be used as opposed to the more common 95% confidence interval.

the user. If a spacecraft component does not have a matching “application” in SEER-H, the user can select an analogous technology and alter the inputs.

For every input in SEER-H, the user defines a "least," "likely," and "most" value corresponding to an optimistic, most likely, and pessimistic assumption for the input. Mass modeling in the present work assumed the "least" value was 95% of the Current Best Estimate (CBE), the "likely" value was the CBE plus the Mass Growth Allowance (MGA), and the "most" input was 30% more than the "likely" input. These assumptions are a slight variation on those recommended in Galorath’s SEER-H Space Guidance document[22]. The SEER-H Space Guidance recommends that the "likely" estimate be equal to the CBE, however, the NASA validation study recommends the "likely" estimate be 95% of the CBE to include the possibility that the spacecraft design will be less massive than the CBE which occurred in 3% of the cases studied by the validation study[20]. The American Institute of Aeronautics and Astronautics (AIAA) American National Standard Mass Properties Control for Space Systems recommends that space missions carry a 30% total margin (including the MGA) prior to Authority to Proceed (ATP) [23]. SEER-H models uncertainty by assigning each “work element” a distribution of possible costs in addition to a median cost. The least/likely/most inputs for each work element correspond to the lower bound, mode, and upper bound of a beta distribution. By default, SEER-H uses the median value of each beta distribution as the input to its CERs. To model uncertainty, SEER-H can also output a Cumulative Distribution Function (CDF), however, SEER-H only outputs the CDF in 10% increments from 10-90%.

SEER-H estimates all the costs associated with the development and production of the hardware elements. This includes system-level costs such as: system engineering, integration assembly and test, program management, and safety and mission assurance. It also includes component-level costs such as requirements capture, design analysis, simulation, layout, verification, prototypes, spares, engineering test, integration, documentation, project engineering, systems engineering, tooling, material, fabrication, integration and assembly, production support, sustaining engineering, and tooling maintenance. SEER-H also models cost savings due to the learning that occurs when producing more than one production unit, this is modeled using Wright’s Cumulative Average Model given by Eq. 1.

$$P_n = P_i N^b \tag{1}$$

The term P_i is the first unit production cost, N is the total number of units produced, P_n is the total cost to produce the N units, and b is a scaling factor between 0 and 1 that determines how much the cost is reduced for each additional unit produced. In SEER-H, each component has its own b value determined by SEER-H’s proprietary database and algorithms.

SEER-H does not estimate the cost of software, maintenance/reuse, propellant, or operations[‡]. The cost of flight software is not included in this work. It is assumed that the difference in software development cost in each architecture is negligible compared to the other costs.

2. PCEC

PCEC is a parametric cost model developed and maintained by NASA[24]. Beginning in 2013, PCEC replaced the legacy NASA/Air Force Cost Model (NAFCOM), utilizing NASA mission data along with data compiled in the One NASA Cost Engineering (ONCE) and REsource Data STorage And Retrieval (REDSTAR) databases, among other sources [17]. These data provide the basis for the PCEC Cost Estimating Relationships. The overall PCEC tool is available as an Excel add-in[25]. Within Excel, the modeling framework may be launched with preset templates for various spacecraft types (e.g. Earth orbiting, planetary, crewed versus uncrewed, and launch vehicle stage). A Work Breakdown Structure (WBS) is then built based on the spacecraft type, usually at a subsystem level (e.g. structures and mechanisms, thermal control, crew accommodations, etc.) although specific components may be included (e.g. tanks, solar arrays, batteries, etc.). After the WBS is set, general parameters are set that impact the total system, such as launch year and design life. Additional inputs are requested for subsystem and/or component CERs, particularly the unit weight, number of units, heritage, development, and testing methodology. System integration costs are based on user-selected analogies from past missions. End results are calculated for a selected base year using the NASA New Start Inflation Index and are given for each WBS element with breakdowns for Design, Development, Testing, and Evaluation (DDT&E) and Production in addition to the point-design totals, which may be modified to include additional program fees and contingency amounts.

[‡] SEER-H does contain CERs for estimating operations and support activities, however, the tool requires knowledge of the mean time between failure of each component on the vehicle, among other inputs. This level of detail for the vehicles being modeled is not currently available.

B. In-space Operations Cost

MOCET was used to estimate an average cost per day of the in-space operations of each spacecraft in this study. Every mission in MOCET's database is a one off requiring significant mission planning. However, the spacecraft in this study will be operating in a large fleet repeating many of the same operations over and over which should reduce the cost per mission. There are very few large-scale fleets of spacecraft, and those that do exist largely maintain a single orbit and do not transport payload. Furthermore, there is no publicly available data on the in-space operations cost of these spacecraft. Therefore, in the absence of data on fleets of spacecraft, the Wright's Cumulative Average Model was used to estimate the cost of operating a repeat mission given by Eq. 2.

$$O_n = O_i N_m^b \tag{2}$$

The term O_i is the in-space operations cost of the first mission obtained using MOCET, N_m is the total number of missions, O_n is the total in-space operations cost of the N_m missions, and b is a scaling factor between 0 and 1 that determines how much the cost is reduced for each subsequent mission. In the absence of data on fleets of spacecraft to compare to, the b value was set to a value consistent with the typical b value given by SEER-H for spacecraft production cost. For more details on MOCET see the following subsection.

1. MOCET

MOCET is an Excel based parametric cost estimating tool developed by The Aerospace Corporation and NASA[18]. MOCET is designed to estimate the cost of the operational portion (Phase E) of NASA science missions. MOCET does not estimate the cost of fuel or spare parts as it is incredibly rare for spacecraft to be serviced in space, rather, MOCET estimates the cost associated with the ground facilities and control personnel controlling the spacecraft. The CERs in MOCET are developed from historic data on the cost of previous NASA missions. The primary inputs to MOCET are the mission type (i.e. planetary, Earth orbiting, etc.) and the duration of various mission phases such as checkout, nominal cruise, orbit insertion, etc.

C. Reuse/Refurbishment Cost

Reuse cost is the cost of refurbishing a hardware element after it has flown and preparing it for its next flight. Since the expendable launch vehicles and SEP tugs are used only once, they do not incur a reuse cost. Likewise, as this study isn't considering the ability to service SEP tugs, even though the SEP tugs are reused in the reusable architecture, they do not incur a reuse cost. The reusable LV first and second stages are the only elements that incur reuse cost.

Normally, the cost of reusing a vehicle is determined by estimating the number of flights each component of the vehicle can be safely used before needing to be inspected, repaired, or replaced. The cost of the component and cost of labor to replace the component is then estimated to provide an estimate of the average cost of maintenance per flight. Such an approach, however, requires data on the life of components and the cost of repairing or replacing them. Currently, reusable spacecraft are an area of rapid innovation by a number of private aerospace companies. Because of proprietary restrictions and the fact that the cost of reuse appears to be rapidly changing, the authors of this work chose a different approach than the traditional cost estimate of the maintenance/reuse of the reusable LV. Instead, the authors used general simplified assumptions based on publicly available information. The authors acknowledge that these assumptions may produce imprecise cost estimates, but should be useful in estimating upper and lower bounds of the reuse cost.

Since a sufficient data set to perform a traditional reuse cost estimate is not available, the authors instead sought to bound the estimate with two polar assumptions; the first representing the current State-of-the-Art (SA) in spacecraft reuse and the second an Extremely Optimistic (EO) view of spacecraft reuse. The SA case is based off of the purported claim that the cost to recover and refurbish a used Falcon 9 rocket first stage was less than 10% of the cost to build the first stage [26]. Thus, each flight of the reusable LV was assumed to cost 10% of its production cost. The EO assumption represents a potential future capability and is based on data from today's commercial airlines. According to the U.S. Department of Transportation's Bureau of Transportation Statistics, fuel costs represent 15-20% of airline expenses. Thus, the EO assumption is that the cost of each flight after development and production costs have been paid will be five times the cost of the CH_4/LOX and H_2/LOX used on the LV (i.e., the cost of the fuel is 20% of the reuse cost). For reference, the cost of CH_4/LOX and H_2/LOX propellant per reusable LV launch was 0.02-0.05% of the production cost of the tanker. Meaning the EO assumption was that 0.1-0.25% of the production cost is paid for each flight, and the EO assumption assumes the reuse cost is 40-100 times less than the SA assumption. While it is extremely unlikely that reusable spacecraft will operate on the economy of scale of commercial airlines, the EO assumption does provide a reasonable lower bound for the reuse cost.

All the results presented in this work use the SA assumptions for reuse. Examining the cost under the EO assumptions will be investigated in future work.

D. Propellant Cost

Propellant cost is the cost of the propellant used by the reusable LVs and the SEP tugs. The cost of Xe and Kr is quite significant with Xe being on the order of thousands of dollars per kg and Kr costing hundreds of dollars per kg. Propellants include Xe, Kr, H_2/LOX, CH_4/LOX, and RP-1/LOX. However, the cost of the chemical propellants, H_2, CH_4, RP-1, and LOX, is less than 0.02% of the total cost in nearly all cases. The cost of the chemical propellants is only included/shown if they account for more than 1% of the total cost of an architecture.

The cost of H_2 and LOX was estimated by adjusting the price NASA paid for these propellants under the Space Shuttle program for inflation. The 2022 cost of liquid CH_4 was obtained from the U.S. Energy Information Administration's website. Finally, the cost of Xe and Kr propellants was taken from a variety of commercial providers. It is important to note that the demand for Xe in the architectures presented in this work is on the same order of magnitude as the current yearly total world production of Xe. The demand for large quantities of Xe could increase the efficiency of Xe production lowering the price, but it is more likely that the increased demand would increase scarcity and also increase the cost of Xe.

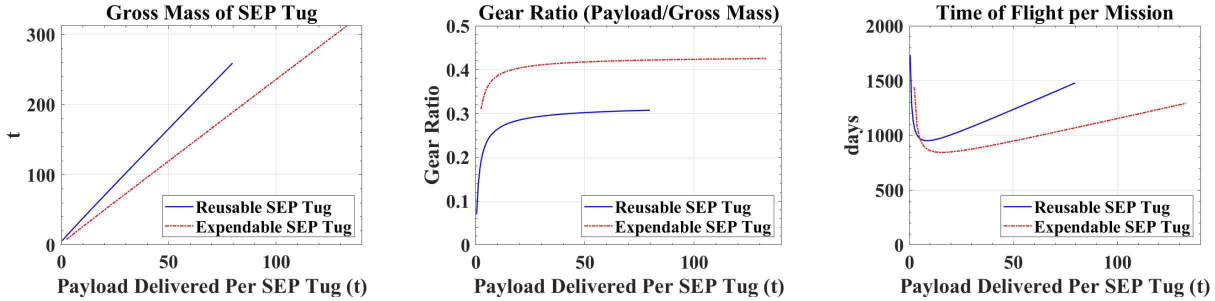
E. Total Cost

The total cost is simply the sum of the development, production, reuse, propellant, and operations costs for a vehicle or architecture. Total costs for a vehicle or architecture are calculated using a combination of Python, Excel, and MATLAB.

V. Results

This section presents the costs associated with delivering payloads to NRHO via reusable or expendable SEP tugs and via reusable or expendable LVs. It is unknown what level of demand there will be for logistics, propellant, or other payloads in NRHO so three campaign scenarios assuming three levels of demand are considered, 250 t, 1,000 t, and 10,000 t. The 250 t and 1,000 t demand levels are respectively the approximate amount of propellant required in NRHO for a conjunction class and opposition class humans to Mars mission. The 10,000 t demand level is beyond the payload required by any mission being considered by NASA and is used to explore the limits of the cost savings of reusability.

First the properties of the SEP tugs are considered. Figure 4 shows the properties of reusable and expendable SEP tugs delivering payload from LEO to NRHO. Both the reusable and expendable SEP tugs have the same design. The difference between them is in the payload that they are capable of carrying. The reusable SEP tugs need enough ΔV to get from LEO to NRHO and back to LEO, while the expendable SEP tugs only need enough propellant to get from LEO to NRHO. As a result, a SEP tug of a certain size will be able to deliver much more payload to NRHO if it is expended rather than being reused. This is demonstrated in Figs. 4a and 4b which show the gross mass of the SEP tugs versus the payload they can deliver and the gear ratio versus payload delivered, respectively. Currently, there is a wide selection of

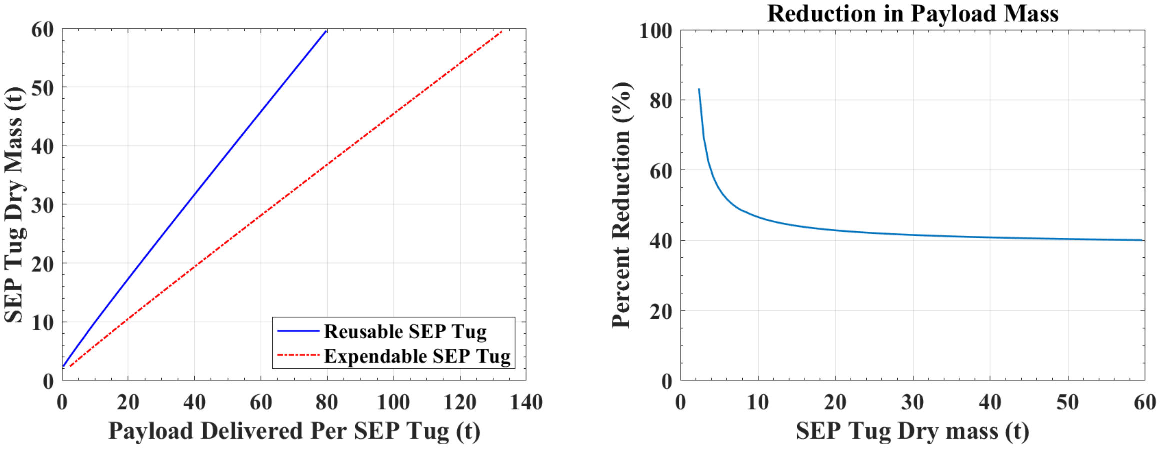


(a) (b) (c)

Fig. 4 Reusable vs. expendable SEP tug properties when delivering payload from LEO to NRHO

expendable LVs on the commercial market. Commercial expendable LVs can deliver payloads to LEO ranging from 0.3-63.8 t. Thus, it is assumed that expendable SEP tugs with a gross mass over 63.8 t will require the development of a super heavy lift expendable LV. According to Fig. 4a, the maximum payload an expendable SEP tug can deliver to NRHO without requiring a new LV to be developed is 26 t. Figure 4a also shows that reusable SEP tugs have a greater gross mass for a given payload delivered. For example, the largest SEP tug in the study can carry an 80 t payload and is limited to a gross mass in LEO of 260 t. However, the exact same SEP tug when used in an expendable configuration can carry 133 t and have a gross mass in LEO of 313 t. The mass advantages of the expendable SEP tugs are made more clear in Fig.4b which shows the gear ratio of each of the expendable and reusable SEP tugs. In this case, the gear ratio is defined as the payload divided by the gross mass, i.e. the fraction of the total mass that is payload. Figure 4b shows that the for larger expendable SEP tugs over 40% of their gross mass is payload, whereas for the same reusable SEP tugs only about 30% of their gross mass is payload. Another important factor with regards to the operation of the SEP tugs is the time of flight it takes a SEP tug to complete a mission. In this context, "mission" is defined as a flight from LEO to NRHO for an expendable SEP tug and a flight from LEO to NRHO and back to LEO for a reusable SEP tug. Figure 4c shows the time of flight per mission as a function of the payload delivered per SEP tug mission for both reusable and expendable SEP tugs. For the expendable SEP tugs, the mission time is the time from launch in LEO to delivering the payload in NRHO as well as a 120 day period after the payload is delivered to allow the SEP tug to move to a disposal orbit. The time of flight for the reusable SEP tugs is greater than that of the expendable SEP tugs, however, each leg of the trip is much shorter. On the flight from LEO to NRHO because the SEP tug is carrying a smaller payload, it is able to complete the trip faster. In addition, on the flight back from NRHO to LEO, the reusable SEP tug is carrying no payload and can make the trip very quickly. Thus, while the reusable SEP tug must travel to and from NRHO, it is able to make the trip in only a few hundred days longer than it takes the expendable SEP tug to reach NRHO.

Ultimately, the factor that determines whether a reusable or expendable architecture is more affordable is the rocket equation. Reusable SEP tugs or LVs need to carry with them the extra mass of the systems and propellant necessary for them to be reused. The extra mass that is needed to make the spacecraft reusable means the vehicle either carries less payload or needs to be scaled up significantly to deliver the same payload. Figure 5 displays this clearly. For example, two identical SEP tugs of the same size, dry mass, propellant, and propulsion capabilities, seen in Fig. 5a, deliver significantly different payloads depending on whether they are expended at NRHO or return back to LEO. Figure 5b shows that for the SEP tugs in this study, the payload reduction required to make a SEP tug reusable is between 40-84%. So while reusing a SEP tug will save on the cost of producing SEP tugs, more missions will have to be flown to deliver the same payload to the customer.



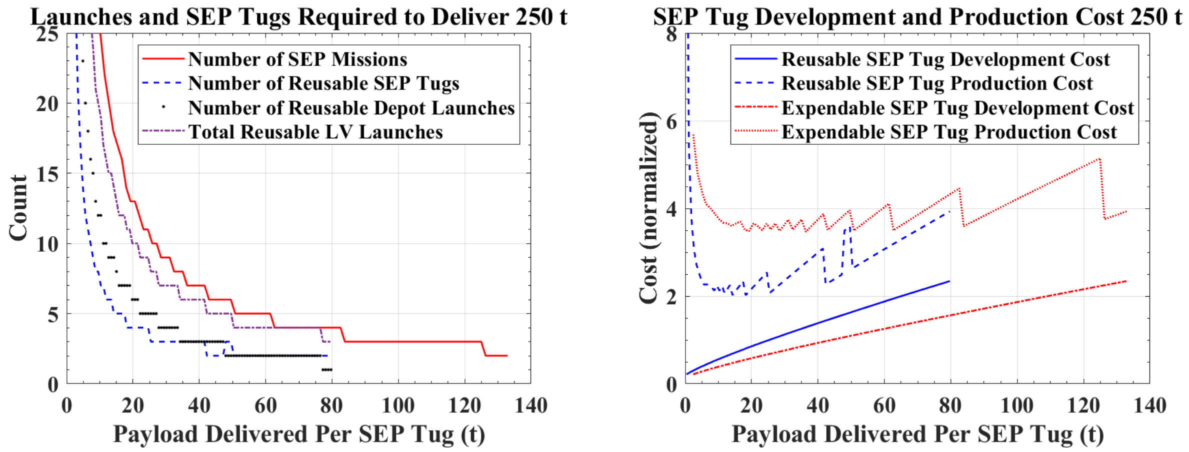
(a)

(b)

Fig. 5 Payload reduction due to reusability for SEP tugs delivering payload to NRHO

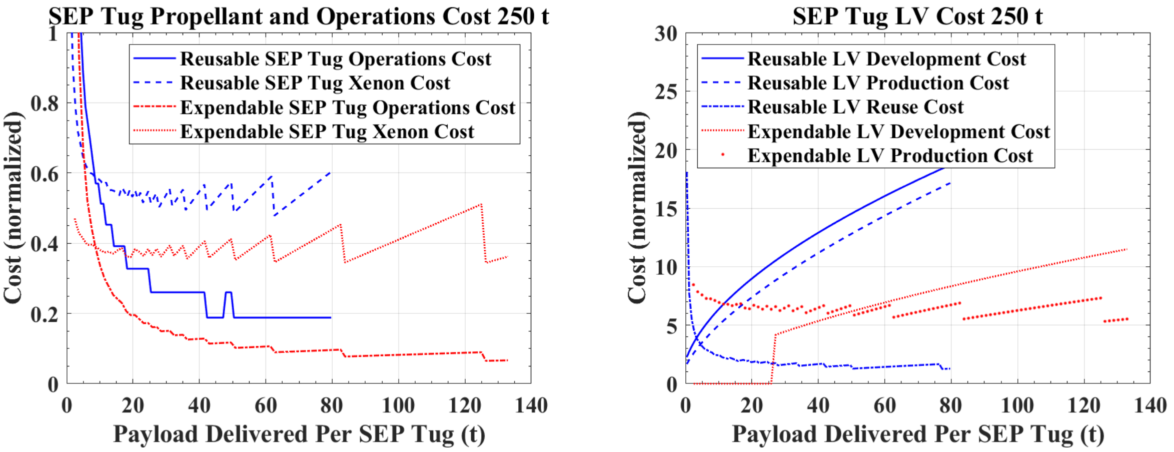
A. Campaign of SEP Tugs Delivering 250 t of Payload to NRHO

Figure 6 shows a series of plots with the costs for each SEP tug and LV design variation in the context of a campaign to deliver 250 t of payload to NRHO. Note that on each plot in Fig. 6, the x-axis displays the payload a single SEP tug



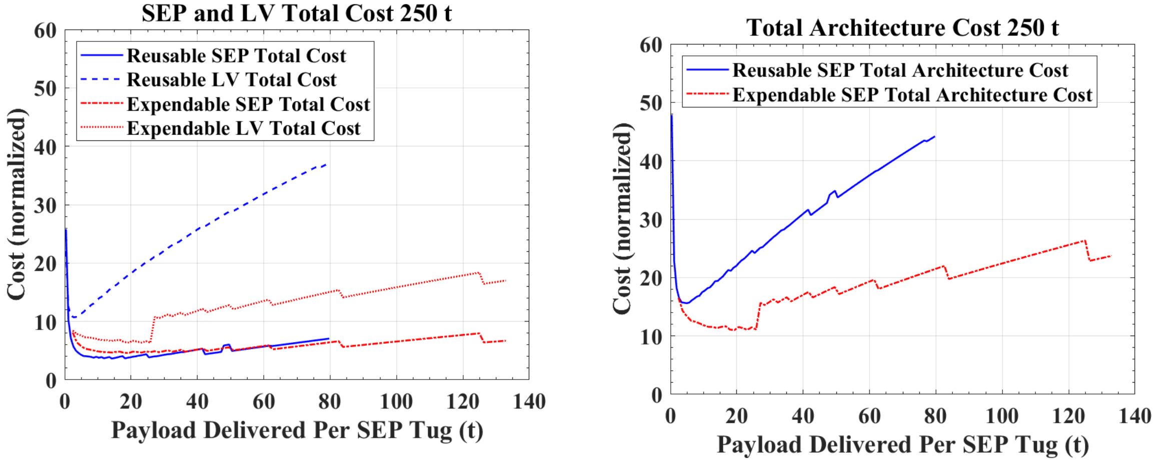
(a) Numbers of missions, spacecraft, and launches associated with the 250 t campaign

(b) Cost of development and production of required number of SEP tugs



(c) Cost of Xe and in-space operations

(d) Launch vehicle development, production, and reuse cost



(e) Total cost of SEP tug spacecraft and launching them to LEO

(f) Total cost of a campaign to send 250 t of payload to NRHO

Fig. 6 Comparison of the number of missions and costs associated with delivering 250 t to NRHO via expendable or reusable SEP tugs

can deliver to NRHO in one mission, and the y-axis displays a cost associated with the varying payload capacity of the SEP tugs. In general, curves representing the expendable architecture are plotted in red, and curves representing the reusable architecture are plotted in blue. The one exception is Fig. 6a which shows the number of missions, SEP tugs, and launches required to send 250 t on the y-axis instead of the cost. In Fig. 6a the solid blue line represents the number of SEP missions required to deliver 250 t to NRHO. This quantity also represents the number of expendable SEP tugs and expendable LVs produced, as for each mission in the expendable architecture, a single SEP tug and LV will be required. Note that the number of SEP missions is simply 250 t divided by the payload delivered per SEP tug, rounded up. Thus, discontinuities in the plot are seen at values where 250 t is evenly divisible. The red dashed line in Fig. 6a shows the number of reusable SEP tugs required to deliver 250 t. It is assumed that each SEP tug will only have a life of 10 years. Thus, a reusable SEP tug capable of completing a mission in under 913 days will be able to complete four missions in its lifetime, whereas a SEP tug taking over 1218 days can only complete a total of two missions in its lifetime. The black dotted line represents the number of reusable second stages serving as refueling depots that will need to be launched to LEO to refuel the SEP tugs. Finally, the dashed/dotted purple line represents the total number of launches required to complete the campaign. Note that despite the fact that the SEP tugs are being reused, there is not a significant reduction in launches by using the fully reusable architecture.

Figure 6b displays the cost of developing and producing the required number of SEP tugs for the 250 t campaign. While the development cost for the reusable SEP tugs is slightly higher than the expendable, the production cost is significantly reduced for the majority of designs. Like in Fig. 6a, the discontinuities in the production cost curves represent the transition from producing one greater or fewer number of SEP tugs.

The cost of the Xe propellant and in-space operations are displayed in Fig. 6c. The cost of both in-space operations and Xe is significantly higher for the reusable architecture as the SEP tugs spend more time in space and require the propellant to return to LEO, however, these costs are an order of magnitude smaller than the development and production costs associated with the SEP tugs.

The costs associated with the reusable and expendable LVs is displayed in Fig. 6d. Note that the cost of developing and producing the LVs is significantly higher than developing and producing the SEP tugs. The development cost of the reusable LV is significantly higher than that of the expendable LV. In addition, the production cost is only less for smaller sized vehicles where the number of required launches is very high. Another advantage of the expendable architecture is that expendable SEP tugs with a gross mass under 63.8 t (payload to NRHO under 26 t) do not require the development of an LV as there are a wide range of expendable LVs already on the market that are capable of delivering these "small" SEP tugs to LEO. The reusable LV also incurs a significant reuse cost. In this case, the cost of reusing the LV is assumed to be 10% of the production cost of the LV. This is consistent with the current state-of-the-art in LV reusability.

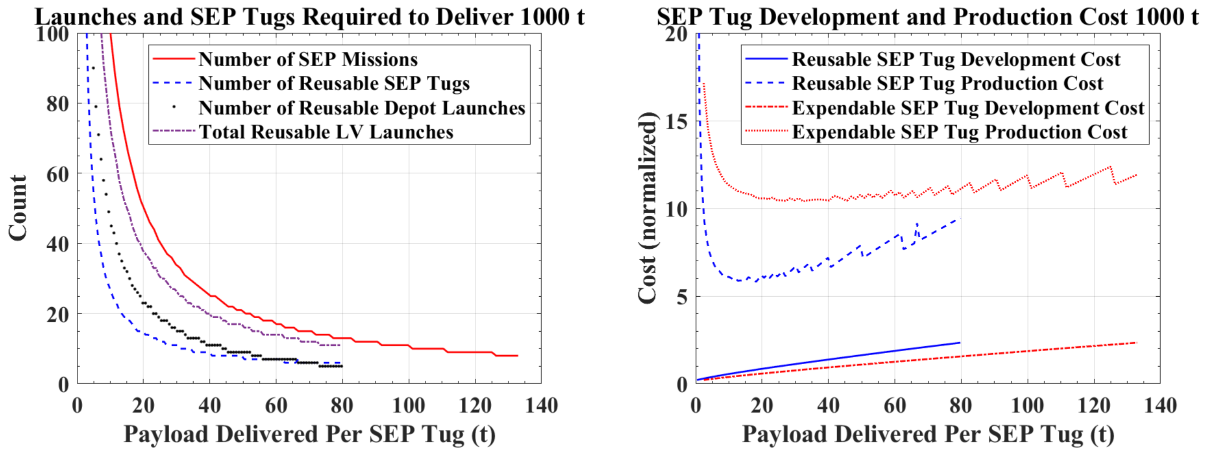
Figure 6e compares the total cost associated with the SEP tugs with the total cost of the launch vehicles. The total cost of the SEP tugs is the sum of development, production, in-space operations, and propellant cost, while the total cost of the LVs is the sum of their development, production, and reuse cost if applicable. The total cost of the reusable SEP tugs is slightly lower than the total for the expendable SEP tugs in most cases. However, the cost of the reusable LVs is significantly higher than the cost of the expendable LVs.

Figure 6f compares the total cost of the reusable and expendable 250 t campaigns. For all cases, the expendable architecture cost less than the reusable, but for SEP tugs with 4 t payload capacity, the costs are approximately equal. For the case of delivering 250 t to NRHO, expendable SEP tugs are the most cost efficient. We will now investigate if this holds true for sending larger payloads to NRHO.

B. Campaign of SEP Tugs Delivering 1,000 t of Payload to NRHO

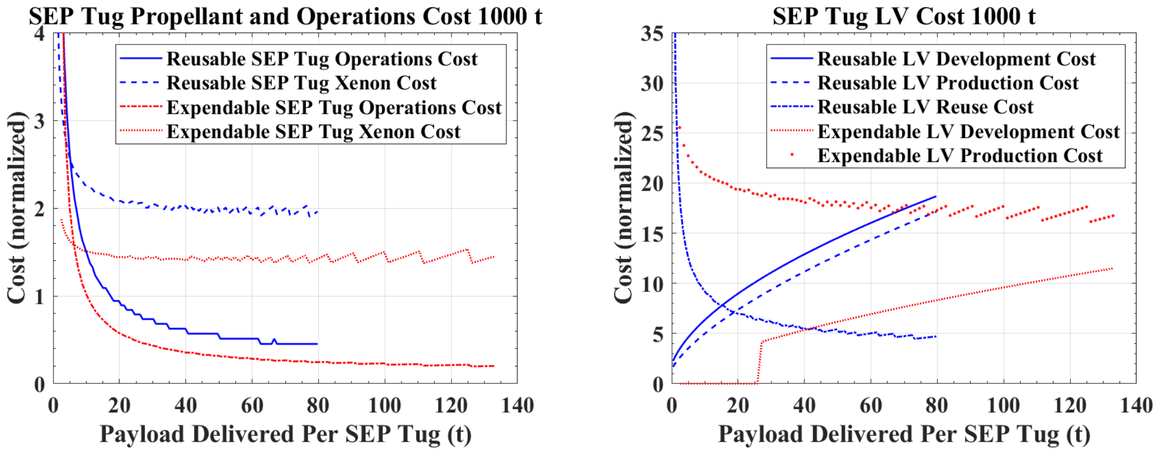
This subsection considers a campaign delivering 1,000 t of payload to NRHO. Previously in the 250 t campaign, the expendable architecture was less costly primarily due to the large upfront development costs incurred by the reusable LVs and refueling depots.

Figure 7 contains the same six plots that were in Fig. 6, but now assuming the total payload delivered to NRHO is four times larger. Figure 7a appears nearly identical to Fig. 6a, however, the number of missions, SEP tugs, depots, and LVs have increased by a factor of approximately four. However, Fig. 7b shows a more significant deviation from the 250 t campaign. For the 1,000 t campaign, the SEP tug production cost has increased significantly while the development costs have remained the same. In addition, the difference in production cost between the expendable and reusable architectures has increased significantly. Comparing Fig. 7c and Fig. 6c shows the trends in in-space operations cost and propellant cost are very similar between the two campaigns. In both campaigns, the cost of in-space operations and propellant is dwarfed by the hardware costs. Figure 7d shows that for all but the largest of LVs, the production cost



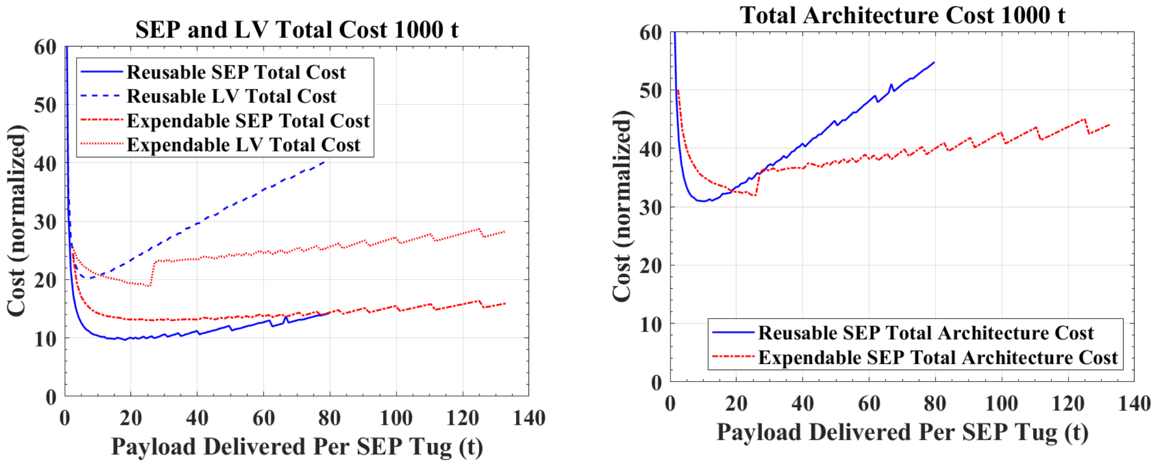
(a) Numbers of missions, spacecraft, and launches associated with the 1,000 t campaign

(b) Cost of development and production of required number of SEP tugs



(c) Cost of Xe and in-space operations

(d) Launch vehicle development, production, and reuse cost



(e) Total cost of SEP tug spacecraft and launch vehicles

(f) Total cost of a campaign to send 1,000 t of payload to NRHO

Fig. 7 Comparison of the number of missions and costs associated with delivering 1,000 t to NRHO via expendable or reusable SEP tugs

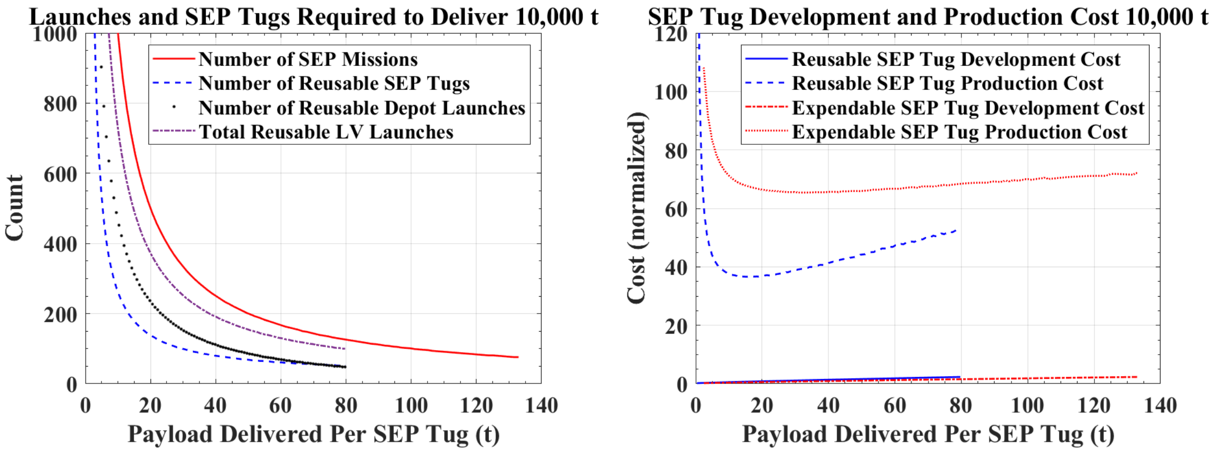
of the expendable LVs is now greater than the development cost of the reusable LVs. This difference in cost between reusable and expendable LVs is made more clear in Fig. 7e which shows that for SEP tug payloads under 10 t, the reusable LVs cost less, but for payloads over 10 t, the expendable LVs are more affordable. However, Fig. 7e also shows that the reusable SEP tugs cost less for nearly all cases.

Finally, Fig. 7f compares the total cost of the expendable and reusable architectures for a 1,000 t campaign. For the 1,000 t campaign, the reusable architecture cost less for SEP tugs delivering under 19 t per mission, while the expendable architecture is more affordable for SEP tugs with higher payload masses. However, the most important thing that Fig. 7f shows is that the minimum cost option for the reusable architecture is approximately equal to the minimum cost option for the expendable architecture. Thus, 1,000 t of payload to NRHO is the "break-even point," above which, the reusable architecture is likely to be more affordable than expendable architecture.

C. Campaign of SEP Tugs Delivering 10,000 t of Payload to NRHO

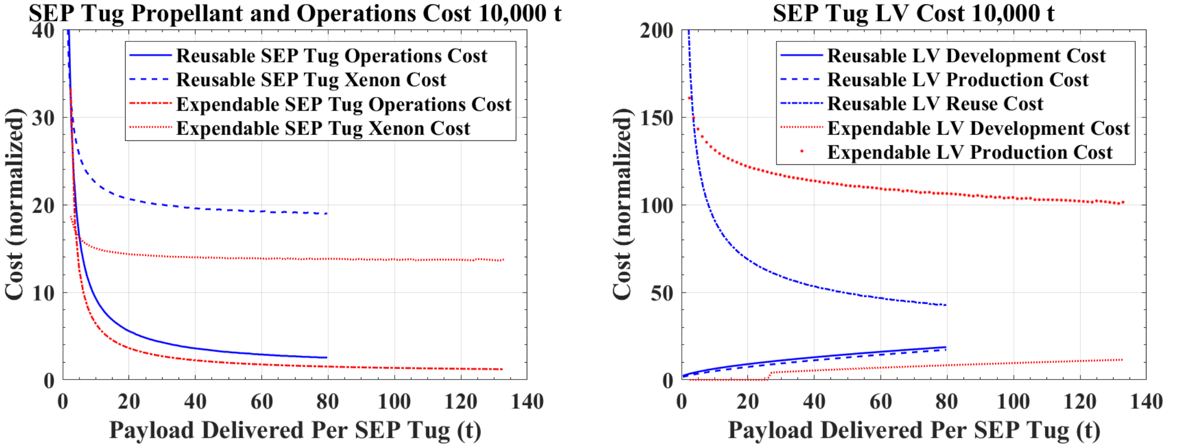
This subsection examines a campaign to send 10,000 t of payload to NRHO. This mass is larger than any mission NASA or any other agency has planned. For example, 10,000 t is the equivalent mass of 22 International Space Stations or 217 Apollo command and service modules and lunar module combinations. The 10,000 t case is not presented because it is part of any planned mission, but because it explores the limits of the cost savings afforded by reusability.

Figure 8 shows the same six plots that were shown for the 250 t and 1,000 t architectures. The trends in Figs. 8a and 8c are similar to those in Figs. 7a and 7c, the primary difference being that the numbers of missions and cost of operations and Xe are approximately ten times higher than in the 1,000 t campaign. Figure 8b shows a similar trend to the smaller campaigns, but now the development cost of the SEP tugs is dwarfed by their production cost. The size of reusable SEP tug with the lowest cost delivers 17 t per mission, while the size that minimized SEP tug production cost for the expendable architecture is 35 t. However, the curve showing expendable SEP tug production cost is relatively flat for payloads over 10 t. Similarly, in Fig. 8d the production cost of the expendable LVs dwarfs its development cost and even dwarfs the development and production cost of the reusable LV. The reuse cost of the reusable LV and the production cost of the expendable LVs are the primary cost drivers of the launch cost in their respective architectures. Figure 8e shows that the total costs of the reusable SEP tugs and LVs are significantly lower than the expendable SEP tugs and LVs. Figure 8 shows that the total cost for the expendable architecture levels out for SEP tugs delivering over 20 t to 200 normalized cost units, whereas the cost of the reusable architecture levels out to around 150 normalized cost units. Meaning, even after delivering 10,000 t of payload, the reusable architecture is only reducing the cost by approximately 25%. Looking at all the plots in Fig. 8 as a whole, the two largest contributors to the cost of the reusable architecture are the SEP tug production cost and the reuse cost of the LV. The next subsection will explore the sensitivities of the reusable architecture.



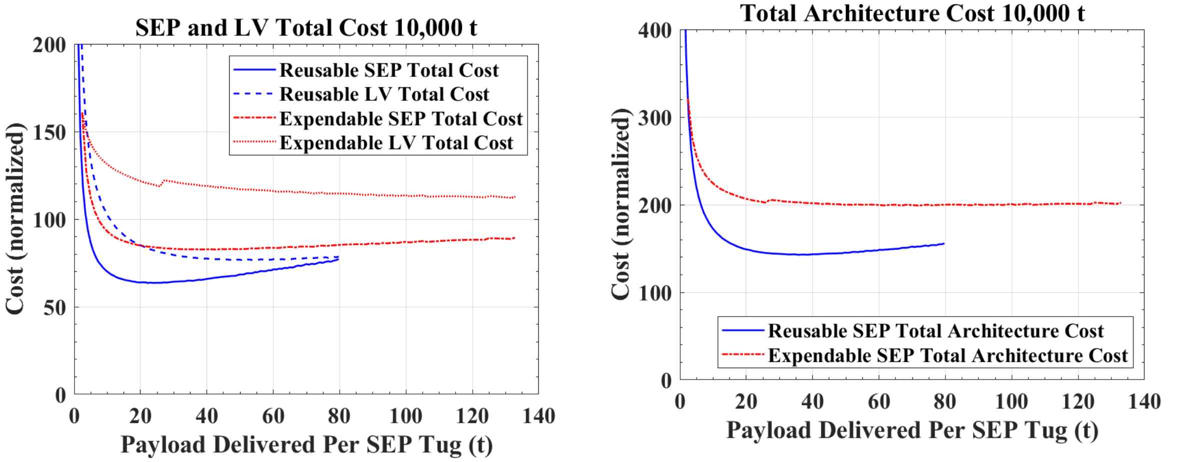
(a) Numbers of missions, spacecraft, and launches associated with the 10,000 t campaign

(b) Cost of development and production of required number of SEP tugs



(c) Cost of Xe and in-space operations

(d) Launch vehicle, development, production, and reuse cost



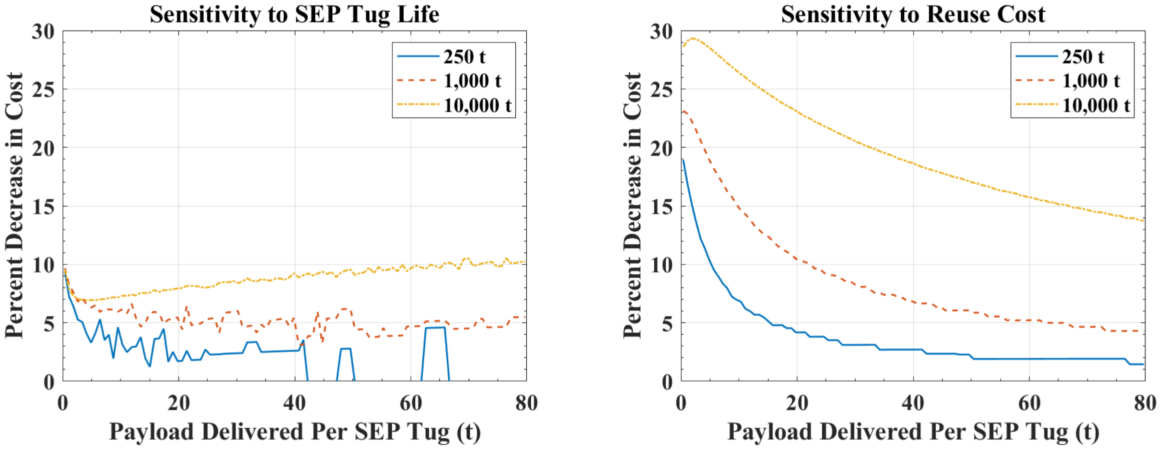
(e) Total cost of SEP tug spacecraft and launch vehicles

(f) Total cost of a campaign to send 10,000 t of payload to NRHO

Fig. 8 Comparison of the costs associated with delivering 10,000 t to NRHO via expendable or reusable SEP tugs

D. Sensitivity to Assumptions

Several parameters that have a major effect on cost in this paper were assumptions made in the absence of usable data. This subsection explores the sensitivity of the cost of the entire architecture to these assumptions. Two of these main factors are the lifespan of the SEP tug and the reuse cost of the reusable launch vehicle. In the previous section, it was made clear that SEP tug production cost and reusable LV reuse cost were the driving factors of the total architecture cost for the 10,000 t campaign. The lifespan of the SEP tugs was previously assumed to be 10 years, and this was chosen as an order of magnitude estimate knowing that the radiation environment in the Van Allen belts would cause the solar panels and other equipment to degrade. Similarly, the assumption that the cost of reusing a LV would be 10% of the production cost of the LV is based on a statement by Elon Musk about the current reuse costs of the Falcon 9 first stage. What if the lifetime of the SEP tugs could be extended to 15 years? What if the reuse cost could be reduced to 5%? These questions are answered in Fig. 9. Figure 9a shows the sensitivity of the total cost of the three campaigns to increasing the lifetime of the SEP tugs to 15 years. For the majority of cases in the 250 t campaign, increasing the lifetime of the SEP tugs reduces the total cost by less than 5%. For the 1,000 t campaign, a 5% reduction in total cost is typical, but for the 10,000 t campaign the cost is reduced by 7-10%. Figure 9b shows that reducing the reuse cost by 50% will have a much greater impact on reducing cost than increasing the life of the SEP tugs by 50%. The cost reduction is particularly high for smaller SEP tug options where more launches are required. Cost reductions of 1.5-19%, 4-23%, and 14-29% can be expected for the 250 t, 1,000 t, and 10,000 t campaigns, respectively. The average cost reduction due to these sensitivities for all campaign options is summarized in Table 1.



(a) Sensitivity of total architecture cost to increasing the life span of the SEP tugs by 50%

(b) Sensitivity of total architecture cost to decreasing the reuse cost by 50%

Fig. 9 Sensitivity of total campaign cost to assumptions in this study

Table 1 Reduction in average total architecture cost by altering assumptions

	Campaign		
	250 t	**1,000 t**	**10,000 t**
Increase life of SEP tug 50%	-2%	-5%	-9%
Reduce reuse cost of LV by 50%	-3%	-9%	-21%

VI. Concluding Remarks and Future Work

Due to the implications of the rocket equation, spacecraft must get exponentially larger as their ΔV requirements grow. Thus, the more ΔV required to reuse a spacecraft, the less likely it is that reusing it will reduce cost. Reusing a LV first stage is the most simple, as the vehicle only needs to carry the extra fuel required to land on Earth, landing gear, and small control surfaces. Reusing a LV second stage is significantly more challenging as the vehicle not only needs to carry extra fuel to deorbit and land, but also requires a heat shield, control surfaces for atmospheric flight, and landing gear. Reusing a dedicated in-space propulsion stage is challenging because the vehicle must be sized to carry significantly more propellant and then additional propellant must be shipped to resupply the in-space propulsion stage. In all of these cases, designing a vehicle to be reusable means either the spacecraft delivers significantly less payload, or the vehicle must be scaled to a much larger size. As the vehicle grows so does the cost of development, production per unit, propellant, and reuse. However, if the system can be reused enough times and the cost of reusing/refurbishing the vehicle is low enough, reusable systems can be more cost effective than expendable ones.

This work examined two competing architectures each with the goal of delivering payload to NRHO. The fully reusable architecture utilized SEP tugs and launch vehicles that carried the necessary systems and extra propellant to allow them to be reused. The fully expendable architecture utilized SEP tugs and launch vehicles that were able to deliver more payload per mission because they did not need to also carry the extra mass of the systems and propellant to allow their reuse. Some key findings of this study are

1) For the application of delivering payload to NRHO via SEP tugs, the break even point where a fully reusable architecture becomes less costly than a fully expendable architecture is after delivering approximately 1,000 t of payload to NRHO.
2) Reusability isn't a "silver bullet" to reduce cost. Even in the 10,000 t campaign, the reusable architecture options were typically only 25% less costly than the fully expendable options.
3) Designing a vehicle to be reusable means either significantly reducing its payload capability or significantly increasing the scale of the vehicle. For two identical SEP tugs, the payload carried to NRHO needs to be reduced by 40-83% for the SEP tug to have enough ΔV to be reusable.
4) For the expendable architecture, the most cost effective SEP tug size to deliver 250 t, 1,000 t or 10,000 t to NRHO is the largest SEP tug that will fit on a commercially available LV. Developing a super-heavy expendable LV exclusively for this purpose will not reduce cost.
5) Increasing the life time of the SEP tugs from 10 to 15 years can reduce the total cost of the reusable architecture by up to 10%.
6) The cost of reusing/refurbishing the reusable LV has the largest effect on the reusable architecture. Reducing the reuse cost by 50% on average decreases the total cost of the reusable 250 t, 1,000 t, and 10,000 t campaigns by 3%, 9% and 21%, respectively.

Sending payload to NRHO via SEP tugs is only one of many possible missions of the Space Superhighway. The cost of delivering payload to other orbits such as GEO should be explored. There are several trades that can be made on the design and operation of the SEP tugs to see how the cost can be reduced. For example, increasing the number of hall thrusters and the size of the solar panels will decrease the time it takes for the SEP tugs to travel to/from NRHO. This will allow the SEP tugs to deliver more payload in their lifetime. In addition, the SEP tugs may take a performance hit by using propellants like Kr instead of Xe, but the reduced cost of these propellants may outweigh the cost increase due to reduced performance of the SEP tugs.

References

[1] Jefferies, S. A., and Merrill, R. G., "Viability of a Reusable In-Space Transportation System," *AIAA SPACE 2015 Conference and Exposition*, 2015, p. 4580.

[2] Craig, D. A., Troutman, P., and Herrmann, N., "Pioneering space through the evolvable Mars campaign," *AIAA Space 2015 Conference and Exposition*, 2015, p. 4409.

[3] Merrill, R. G., Chai, P., Jones, C. A., Komar, D., and Qu, M., "An Integrated Hybrid Transportation Architecture for Human Mars Expeditions," *AIAA SPACE 2015 Conference and Exposition*, 2015, p. 4442.

[4] Reed, B. B., Smith, R. C., Naasz, B. J., Pellegrino, J. F., and Bacon, C. E., "The restore-L servicing mission," *AIAA space 2016*, 2016, p. 5478.

[5] Doggett, W. R., Dorsey, J. T., Jones, T. C., and King, B., "Development of a tendon-actuated lightweight in-space MANipulator (TALISMAN)," *The 42nd Aerospace Mechanism Symposium*, 2014.

[6] Cooper, J. R., Neilan, J. H., Mahlin, M., and White, L. M., "Assemblers: A Modular, Reconfigurable Manipulator for Autonomous in-Space Assembly," *ASCEND 2020*, 2020, p. 4132.

[7] Friz, J. S., Kenney, P. S., and Neuhaus, J. R., "Modeling Conservation of Angular Momentum for Robotic In-Space Assembly Systems," *AIAA Scitech 2020 Forum*, 2020, p. 2270.

[8] Neilan, J. H., Cooper, J. R., and Mahlin, M., "Testing and evaluation of a modular and reconfigurable manipulator for autonomous in-space assembly," *AIAA SCITECH 2022 Forum*, 2022, p. 0626.

[9] Owens, A., and De Weck, O., "Systems Analysis of In-Space Manufacturing Applications for the International Space Station and the Evolvable Mars Campaign," *AIAA SPACE 2016*, 2016, p. 5394.

[10] Tiffin, D., and Friz, P. D., "Parametric Cost Analysis of Expendable vs. Reusable Refueling Architectures in Cis-Lunar Space," *ASCEND 2021*, 2021, p. 4066.

[11] Tiffin, D., Friz, P. D., and Narciso, A., "The Space Superhighway: Building an In-Space Logistics Resupply Network," *ASCEND 2022*, 2022, p. 4066.

[12] Edelbaum, T. N., "Propulsion requirements for controllable satellites," *Ars Journal*, Vol. 31, No. 8, 1961, pp. 1079–1089.

[13] Kluever, C. A., "Using edelbaum's method to compute Low-Thrust transfers with earth-shadow eclipses," *Journal of Guidance, Control, and Dynamics*, Vol. 34, No. 1, 2011, pp. 300–303.

[14] Komar, D., Hoffman, J., Olds, A., and Seal, M., "Framework for the Parametric System Modeling of Space Exploration Architectures," *AIAA Space 2008 Conference & Exposition*, 2008, p. 7845. doi:10.2514/6.2008-7845.

[15] Friz, P. D., Samareh, J. A., and Hosder, S., "New Method for Systems and Cost Analysis of Human Mars Entry Vehicles," *Journal of Spacecraft and Rockets*, Vol. 56, No. 6, 2019, pp. 1742–1756.

[16] Friz, P. D., Samareh, J., and Hosder, S., "A Cost Modeling Approach for Entry Systems Analysis of Human Mars Missions," *2018 AIAA SPACE and Astronautics Forum and Exposition*, 2018, p. 5177.

[17] NASA, *NASA Project Cost Estimating Capability Overview for GAO*, NASA Marshal Spaceflight Center Engineering Cost Office, 2016.

[18] Hayhurst, M. R., Wood, B. W., Eftekharzadeh, S., Daniels, C. L., Jordin, L. M., Sasamoto, W. A., and Rodriguez, W. J., "Mission Operations Cost Estimation Tool (MOCET)," *2017 IEEE Aerospace Conference*, IEEE, 2017, pp. 1–13.

[19] Sanchez, S., and Kha, K., "SEER Validation Study Results for NASA Space Science Missions," *NASA Cost Symposium*, Galorath Inc., 2015.

[20] Friz, P. D., Hosder, S., Leser, B. B., and Towle, B. C., "Blind validation study of parametric cost estimation tool SEER-H for NASA space missions," *Acta Astronautica*, Vol. 166, 2020, pp. 358–368.

[21] Friz, P. D., Klovstad, J. J., Leser, B. B., Towle, B. C., and Hosder, S., "Blind Study Validating Parametric Costing Tools Price TruePlanning and SEER-H for NASA Science Missions," *21st AIAA Space Conference*, 2018. doi:10.2514/6.2018-5178.

[22] Galorath, *SEER-H Space Guidance: Revision 2.2*, Galorath Inc., 2016.

[23] “American National Standard: Mass Properties Control for Space Systems,” 2015.

[24] Alford, B., and Prince, A., “NASA project cost estimating capability: New analyses for spacecraft estimating,” 2016.

[25] Prince, A., Alford, B., Boswell, B., Pitlyk, M., and Pedigo, M., “Development of a Project Cost Estimating Capability,” *NASA Cost Symposium*, 2014.

[26] Musk, E., “Twitter Post: Payload reduction due to reusability of booster & fairing is <40% for F9 & recovery & refurb is <10%, so you’re roughly even with 2 flights, definitely ahead with 3,” @elonmusk, August 18 2020.