Trade-off Analysis of ROI for Capability Stepping-Stones to a Lunar Habitat

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Abstract— **As mankind continues to progress, a logical next step is the expansion into space. Independent space enterprises are developing capabilities to support: space tourism, space debris collection, low earth orbit (LEO) habitats, lunar visits, and temporary/permanent lunar habitats. The structure of the space market has created an industry structure such that activities are independent, are not coordinated, and do not consider leveraging adjacent capabilities. For example, insurance costs are determined based on individual capabilities and do not take into account synergies and liability mitigation to reduce risk from adjacent capabilities. This project evaluates the return on investment from coordination of activities to create "capability stepping-stones" from the five independent capabilities listed above to develop a lunar habitat. A decision support tool that utilizes discrete-event simulation was developed to estimate the ROI from alternate investment, direct operating, indirect costs, and revenues to determine cost, time, and risk thresholds to achieve ROI financial targets. This model is based on data from peer-reviewed government and industry sources such as DARPA, NASA, and the ESA and includes quarterly computation of Net Present Value (NPV). Data and inputs for the decision support tool were used where available. Trade-off analysis indicates the necessity of debris collection, and the importance of lowering launch costs on the development of space. One of the major factors achieved through capability stepping-stones is lowering of launch costs, insurance costs and reversal of the declining trend of LEO conditions. These results indicate an important role for international governance and collaboration between capability stepping-stones of the space-market place to maximize the potential of space.**

I. Introduction

A. Benefits of Space

MANY technological advances were developed during the Space Race coinciding with the Cold War. Advances in technology gave us many new devices such as the CAT and MRI machines used in hospitals across the globe. The Space Race also provided the technologies for developing the personal computer, a key tool of our time.

Space provides the next step for humanity, the final step in exploration for mankind. Space provides many unique opportunities for the inhabitants of Earth: new jobs, new technologies, and new ideas. Establishing a new space market will provide much needed economic growth to help raise the standard of living across the globe. Through the further development and habitation of space, it would likely be seen even greater advancements in technologies as we work to develop those that will be necessary to achieve a sustainable life in space. New ideas will lead to better technologies that will in turn help the people of Earth live a better life.

B. Past and Current Investments

United States investment in space since 1958 has decline [1]. During the mid-1960s, NASA had its largest federal budget at 5.5% as a percentage of the GDP. During this time period, many new technologies were developed that culminated with putting the first men on the Moon. Since then, the annual percentage of the federal budget for NASA has fallen significantly, reaching a point of 0.48% of the GDP for the current 2012 NASA budget, one tenth of NASA's peak budget in the 1960s.

This decline in budget allotment can be attributed primarily to lack of interest or change in priorities by people, government, and the private sector regarding space programs. Without motivation for space development, interest in space has diminished. Interest in the development of space translates to investment, so garnering interest in space is necessary.

Private investments are at an all time high, with several companies around the world collectively investing 100-180 million dollars of their own resources, towards developing space technologies [2]. Some of the more notable companies are: Virgin Galactic, Bigelow Aerospace, SpaceX, STI, ULA and XCOR. Each company has its own space objectives and goals, that when used together can optimize the development and expansion of space habitation.

However, before any of this can happen, collaboration must occur among industries that will reduce the duplication of technologies and the waste of investment. Through collaboration, avoiding the process of "reinventing the wheel" will be paramount in effective capital investment, while maximizing ROI possible.

C. Potential Outcomes

The capabilities necessary to achieve a permanent, sustainable presence on the Moon are based on five key functionalities: launch, hazard mitigation, space travel, habitation, and sustainability.

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1) *Launch:* The ability to launch supplies, personnel, and equipment from Earth is integral to any initial space endeavor.
2) *Hazard mitigation:* After escaping Earth's gravity, the ability to mitigate risk from both natural and man-made hazards in space takes precedence.
3) *Space travel:* Space travel is also important to consider. The average distance to the Moon from the Earth is 384,400km, a distance that required just under 76 hours of travel time for the astronauts of the Apollo 11 missions [3].
4) *Habitation:* Once on the Moon, with temperatures ranging from -233 to 133 degrees Celsius on the surface, habitation of its inhospitable environment of the Moon is the next step [3].
5) *Sustainability:* Sustainability of this habitation, as well as all previous functionalities is then necessary to the development of a permanent presence on the Moon. This sustainability also includes maintaining ship integrity upon re-entry into the Earth's atmosphere, and maintaining the integrity and operation of a lunar habitat amidst a radiation storm, for example.

D. Obstacles

While conditions and travel time to the Moon can be managed, certain elements of the aforementioned functionalities present obstacles to be overcome. These obstacles are social, environmental, and technological in nature.

II. Industry Limitations

A. Capital Investment

The main problem facing industries attempting to promote a space market is the lack of interest exhibited by governments and the Earth's population. Government's disinterest can be quantified by a lack of NASA funding compared to 1962 through 1970 during the Space Race. This lack of interest may have propagated from the general public. According to a poll conducted by TIPP in 2011, only 10% of respondents showed interest in raising NASA's budget [4]. The origin of this lack of interest is a focus on near-term problems such as the state of the economy. This lack of interest is exacerbated by doubt surrounding the feasibility of the development of space, and the benefit versus the risk of space.

B. Debris

Since the start of the space race in the 1960s, governments and private industries has been launching satellites to orbit Earth. As of 2011, NASA was tracking 22,000 pieces of debris, each larger than 4 inches in length, an increase of 3,000 from NASA's 2006 numbers [5],[6],[7].

NASA can only track debris larger than 10 cm in diameter, and estimates that there are 500,000 pieces of debris diameters ranging from 1 to 10 cm. These debris travel at up to speeds of 28,163 kph [8] and are easily capable of damaging spacecraft and satellites.

Scientists indicate that the quantity of space debris has reached a critical level [9]. Hugh Lewis, a UK researcher, warned that threat from space debris would rise 50% in the decade and quadruple in the next 50 years [10]. According to an NRO study, by 2020, the probability of a catastrophic collision would be at 10% in LEO [11]. If this problem is not addressed, the insurance cost associated with protecting people and assets would greatly increase.

C. Launch Costs

The projected launch cost into space is under $1,000 per pound using SpaceX Falcon Heavy rocket with four launches per year [12]. This cost is the biggest hurdle preventing mankind from quickly expanding into space. For example, assuming the Falcon Heavy had a full payload of 53,000 kg (117,000 lb) the cost to launch would be $117 million. Note, too, that this projection is optimistic compared to previous launch cost indices. As a point of reference, the NASA space shuttle launch cost index is $4729 in 2002, or over $6000/lb with added inflation [13]. Fortunately, an increase in launch frequency will help drive down the cost index by lowering costs related to maintaining idle components. Bulk launch contracts also qualify for discounts from certain launch companies, such as SpaceX. In lieu of breakthrough technological advances, which won't be considered for this project, these approaches to lowering the launch cost index must suffice.

III. Stepping-Stone Design

After conducting research concerning the environment surrounding a potential space market, a sequence of capability stepping-stones was developed. These stepping-stones focus on combining the necessary capabilities of an industry or industries to overcome the hurdles of launch cost, debris, and interest while providing that industry or industries the specified ROI. Each stepping-stone requires the previous stepping-stone to be established before the next stepping-stone could be enacted. These stepping-stones include high-altitude tourism, debris collection, LEO habitats, and LEO hub and Moon base, leading ultimately to a permanent lunar habitat.

A. High Altitude Tourism

Based around Virgin Galactic mission plan, these high altitude tourism trips focus on bringing in the initial round of investments to space companies. This investment spurs the construction of various spaceports, and pushes other industries to recognize future profit from investing in space markets. This stepping-stone also serves as a catalyst for fostering an interest in space in the general public. This excitement to go into space is key to make the following stepping-stones achievable.

B. *Debris Collection*

The potential of a catastrophic collision from space debris continues to grow. Progress into space will become increasingly encumbered by insurance costs should debris collection fail to take place. Logically, before LEO can become habitable, the majority of space debris in LEO needs to be removed. This debris has the potential to be returned to Earth for reselling or recycling depending on the value of the debris. By removing large amounts of the debris that is orbiting in LEO, the insurance factor for both assets and humans would be reduced during LEO habitation.

C. *LEO Habitation*

With the two previous stepping-stones complete, LEO human habitation becomes possible. Now there would be an interest in space from both the public and also governments, most of the necessary ground framework would have been established, and the risk of catastrophic orbital collisions reduced. Based on Bigelow Aerospace's mission plan, this presence in space allows for both scientific research as well as short-term space vacations for the public. As the amount of LEO habitats increases, the cost for launching reduces, thus making it more accessible to a larger portion of the public. As the number of LEO habitats increases, our ability to sustain life at LEO is developed.

D. *LEO Hub and Moon Base*

One of the advantages of the LEO habitats utilized in the previous stepping-stone is the modularity of the habitats. Bigelow Aerospace BA-330s can be connected together, so the concept of creating a space station or hub from piecing together these habitats is logical. This space station will become the platform for further exploration into space. By utilizing a LEO space station, a space-exclusive travel vehicle would be capable of quickly and efficiently move through space to a similarly constructed lunar base. The purpose of space-exclusive ships is to mitigate the frequency of reentry into the atmosphere which can damage ships, and to utilize alternative fuels that do not require fuel to be launched from Earth. This lunar base sets the groundwork for a permanent lunar habitat.

Revenue is obtained through tickets to both the LEO hub and the lunar base. Traditional launch vehicles would be used to get tourists to the LEO hub. From there, the space-exclusive travel vehicles would taxi Moon-bound tourists.

E. *Permanent Lunar Habitat*

The expansion of the lunar habitat to a permanent status requires utilizing the materials available on the Moon. While certain components, such as nitrogen still need to be sent from Earth, basic materials necessary for sustaining life, such as water and oxygen, can be harvested from lunar regolith. This permanent lunar habitat represents the goal of the project, and seeks to utilize mining and manufacturing to establish a permanent presence on the Moon, and create a platform delving deeper into space and capturing and utilizing resources of other celestial bodies.

IV. Methodology

A. *Modeling*

To allow trade-off analysis and the removal of certain capabilities, each model was constructed independently, and then combined together. This approach allows stepping-stones to be modeled either as a strict series of the stepping-stones or have them overlap to show the effects of a stepping-stone on the adjacent stepping-stones. The focus of each model is to show how parameter manipulation affects the ROI for that stepping-stone.

B. *Design*

A single-string design was selected for this project. This series of stepping-stones addresses the problems mentioned in section II, and attempting to analyze the cost of a permanent lunar base without first establishing these specified capabilities was deemed too abstract to quantify.

Each model was constructed in SPEC Innovation's NimbusSE functional database & modeler, where developing logic is visual, and where ROI equations can be broken down into assets with cost, schedule, and performance characteristics.

C. *Equations*

Throughout the simulation, all cost calculations were done using Net Present Value (NPV), with an inflation rate of 3% per year and a saved rate of 4% per year. The primary equation for each stepping-stone is discussed below. However, often there are secondary equations within the models, calculating demand increase/decrease, cost rate changes, or performance increases.

1) *High Altitude Tourism:* The primary equation for this stepping-stone is the ROI equation (1). The equation assumes that there is a consistent demand for trips and is only limited by the performance of the vehicle. The summation of the investments includes parameters: development costs, ship costs, mission costs, maintenance costs, and decommissioning costs.

$$ROI = (\sum Revenue - \sum Investments)/\sum Investments \quad (1)$$

2) *Debris Collection:* Stepping-stone 2 builds on high-altitude tourism thus the ROI equation is carried over. In addition the ROI equation (2) models the amount of debris collected over time is included. Variable definitions are included in Table I.

$$x_{i+1} = x_i - n * R * e \quad (2)$$

TABLE I
DEBRIS COLLECTION VARIABLES

Variable	Meaning
X_i	Debris in orbit
X_{i+1}	Debris in orbit after time step
n	Number of active debris collectors
r	Rate of collection
e	Efficiency of collection

The rate of collection (r) is identified as the pounds of debris collected over a 24-hour period. The efficiency of collection (e) acts as a difficulty factor for collecting debris based on its abundance. While the amount of debris is large, debris collection is simple. As the debris is collected, the value begins to drop also. The minimum efficiency was chosen to be .3 (notional), while the maximum efficiency is 1.

The equation for this (3), is a logistic curve, shown below, that represents a notional idea of debris collection efficiency.

$$e = 0.7/(1 + e^{0.004x_i+5}) + 0.3 \tag{3}$$

3) *LEO Habitat:* The profit equation (4), for this stepping-stone takes the perspective of the industry leasing LEO Habitats to governments, other industries, and individuals. This equation does not include the cost for the renter to launch to the habitat, but does include the maintenance cost to send a specialist to fix any problems with the habitat; variable definitions are in Table II.

$$Profit = P * n - [C_h n + C_{LH}\left(\frac{L_h}{MTBF_h}\right) + \frac{1}{6}C_{LP}\left(\frac{L_h}{MTBF_h}\right)] \tag{4}$$

TABLE II
LEO HABITAT VARIABLES

Variable	Meaning
P	Habitat lease price
C_h	Cost of habitat
C_{LH}	Cost to launch habitat
C_{LP}	Cost to launch person to habitat
C_{MN}	Maintenance cost
L_h	Lifetime of habitat
$MTBF_H$	Habitat failure rate
n	Number of habitats

4) *LEO Hub & Moon Base:* The profit equation (5), for stepping-stone 4 follows the general formula from stepping-stone 1. The only variations are the destination of the travelers, and the number of elements considered; ticket sales are for trips to the LEO hub, or to the Moon base. The investment portion of the equation is comprised of the cost, launch cost, and maintenance costs of both the LEO hub and the Moon base, and the cost, launch cost, and maintenance costs of both the Earth-hub ships, and hub-Moon base space-exclusive ships. As in the LEO habitats stepping-stone, number of maintenance events is dictated by the lifespan of the element divided by the mean time between failure of the element. The equation is seen here and variables are in Table III.

$$\begin{aligned} Profit = {} & T_H P_{TH} + T_M P_{TM} + C_{L,H} + C_{L,MB} + xC_x + yC_y \\ & + \frac{T_H}{Cap_x} C_{Lx} + \frac{T_{MB}}{Cap_Y} C_{Ly} + x\frac{L_x}{MTBF_x} C_{M,x} + y\frac{L_y}{MTBF_y} C_{M,y}) \end{aligned} \tag{5}$$

TABLE III
LEO HUB & MOON BASE VARIABLES

Variable	Meaning
T_h	Ticket to LEO hub
P_{th}	Price of Ticket to LEO hub
T_M	Ticket to Moon base
P_{TM}	Price of Ticket to Moon base
C_H	Cost of LEO hub
C_{MB}	Cost of Moon base
L_{MB}	Lifetime of Moon base
$MTBF_{MB}$	Moon Base Failure Rate
$C_{M,MB}$	Average Cost to fix Moon base
L_H	Lifetime of LEO hub
$MTBF_H$	Moon Base Failure Rate
$C_{M,H}$	Average Cost to fix LEO hub
$C_{L,H}$	Cost to Launch LEO hub
$C_{L,MB}$	Cost to Launch Moon base
x	Number of Earth-LEO hub ships
y	Number of LEO hub-Moon base ships
C_x	Cost of Earth-LEO hub ship
C_y	Cost of LEO hub-Moon base ship
Cap_x	Capacity of Earth-LEO hub ship
Cap_y	Capacity of LEO hub-Moon base ship
C_{LX}	Launch Cost for Earth-LEO hub ship
C_{LY}	Launch Cost for LEO hub-Moon base ship
L_x	Lifetime of Earth-LEO hub ship
$MTBF_x$	Earth-LEO hub ship failure rate
$C_{M,x}$	Average Cost to fix Earth-LEO hub ship
L_y	Lifetime of Earth-LEO hub ship
$MTBF_y$	LEO hub-Moon base ship failure rate
$C_{M,y}$	Average Cost to fix LEO hub-Moon base ship

5) *Permanent Lunar Base:* The profit equation (6), for a permanent lunar habitat includes life-cycle costs for Moon mining and manufacturing, as well as costs for moving equipment and personnel on the Moon. Variable definitions are included in Table IV.

$$\begin{aligned} Profit = {} & \\ \textstyle\sum_{yrs}(R * n) - C_{B+E} - \sum_{yrs}(C_o + C_m + C_t * P * T) \end{aligned} \tag{6}$$

TABLE IV
PERMANENT LUNAR HABITAT VARIABLES

Variable	Meaning
R	Average Regolith Payload
n	Number of Payloads
C_{B+E}	Cost of Base & Equipment
C_o	Operating Costs/year
C_m	Maintenance Costs/year
C_t	Travel Cost on Moon/lb
P	Average Payload
T	Number of Trips/year

Note that equation (6) includes both annual costs and the one-time cost of the base and mining equipment, and launching the base and equipment to the Moon.

V. RESULTS

Due to the nature of data disclosure in the private industry, it is assumed that a company will enter their own values for inputs to the models. Where unavailable, notional values for inputs were entered into the simulation. The purpose of these results is to illustrate the output of the models.

A. High Altitude Tourism

Where available, data was based on Virgin Galactic's mission plan. Cost per ticket is assumed to be a constant $200,000, capacity of 6 passengers per flight, and $100,000,000 initial investment [2]. Other inputs taken into the simulation are entered by the user, as seen in Table V.

TABLE V
HIGH ALTITUDE TOURISM INPUT VALUES

Input	Value
Direct mission cost	$400,000
Flights per month (demand)	2
Flights per maintenance	2
Maintenance Cost	$50,000
Maintenance time	2 weeks

Using Virgin Galactic as the basis the model is produces a positive ROI is with in 5 years. Note that the simulation assumes one ship is used for the simulation.

B. Debris Collection

Simulation of the debris collection model shows that the investment cost from stepping-stones can be reduced. When modeled on a non-LEO orbiting vehicle, the potential savings is $10 million over five years.

C. LEO Habitat

With interest increased and the conditions of LEO improved through debris collection, the ROI for a potential LEO habitat provider, such as Bigelow Aerospace, is calculated. This simulation addresses the full life cycle of a habitat, and assumes a positive demand for the habitats, resulting from an increased interest due to the high altitude tourism stepping-stone. The inputs for this stepping-stone are viewed in Table VII.

TABLE VII
LEO HABITAT INPUT VALUES

Input	Value
Initial Investment	$200,000,000
Lease Revenue	120,000,000 over 5 Years, 50% up front
Maintenance Cost	N(800000000,2000000)
Frequency of Launch to Habitats	3 per year per habitat
Demand	2 Habitats per year
Initial Launch Cost	$1000/lb
Minimum Launch Cost (after frequency benefit)	$700/lb

Using these values, the LEO habitat model achieved a positive ROI within 10 years. The limiting factor for this model is the habitat construction rate. If the construction rate was increased, this model meets ROI in the necessary time duration.

D. Hub and Moon Base

Utilizing the reduced launch costs, and interest from government and private industry attained from the previous stepping-stone, the hub and Moon base stepping-stone can achieve an ROI in around eight years. Model input assumptions are viewed in Table VII.

TABLE VII
HUB AND MOON BASE INPUT VALUES

Input	Value
Initial Investment	$200,000,000
Initial Habitat count (hub)	8
Ticket price to LEO hub	$50,000
Ticket price to Moon base	$200,000
Cost of Space-only Ship	$100,000,000
Launch cost/lb for Space-only Ships	$100/lb
Initial Launch Cost/lb for Earth-Hub Ships	$750/lb
Min Launch Cost/lb for Hub-Moon base Ships	$500/lb
Launches to LEO hub per time period	150/yr (average)
Launches to Moon base from LEO hub	60/year (average)

E. Permanent Lunar Habitat

With tourism to the Moon established from the LEO hub and Moon base stepping-stone, the final step is begin utilizing the resources of the Moon to create a self-sustainable lunar base. Sample input parameters are viewed in Table VIII.

TABLE VIII
PERMANENT LUNAR HABITAT INPUT VARIABLES

Input	Value
Initial Investment	$800,000,000
Regolith Harvested	160k Tons/year
Maintenance Cost for Equipment	$50,000,000
Time between Maintenance	2.5 Years
Operational cost for Base	N(100000000,25000000)/year
Travel Cost on Moon	$100/lb
Number of Initial people at Lunar Base	50
Number of people increase per year	20 (average)

Given these input parameters, the simulation shows a positive return on investment does not occur within a span of 13 years.

VI. TRADE-OFF ANALYSIS

A. Debris Removal

In order to reduce orbital insurance rates for LEO Habitats debris collection need to occur. Fig. 1 shows the required investment using the same inputs on LEO Habitats for both debris collection occurring and debris collection not occurring. If debris collection does not occur the total investment need from a LEO habitat provider would be an estimated $1 billion more over 12 years, then if debris collection did occur.

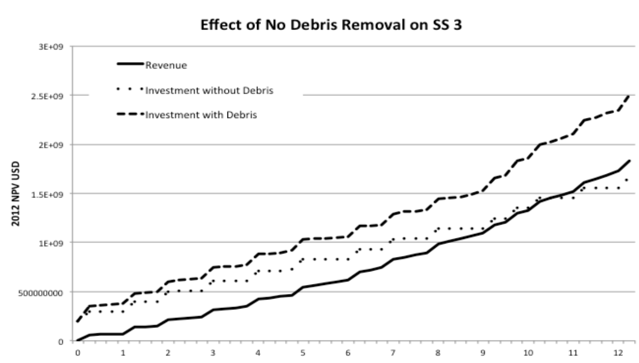

Fig. 1. Effect of Debris Removal on LEO Habitat Investment

B. *Mining vs. No Mining on the Moon*

Despite the large period of time before an ROI can be obtained when considering the permanent lunar base, it is important to note the value of mining and manufacturing on the Moon. As shown in Fig. 2, if one simply considers the cost of launching the iron, aluminum, oxygen, water, and other materials from Earth, the investment required is roughly 1.8 billion dollars higher after six years.

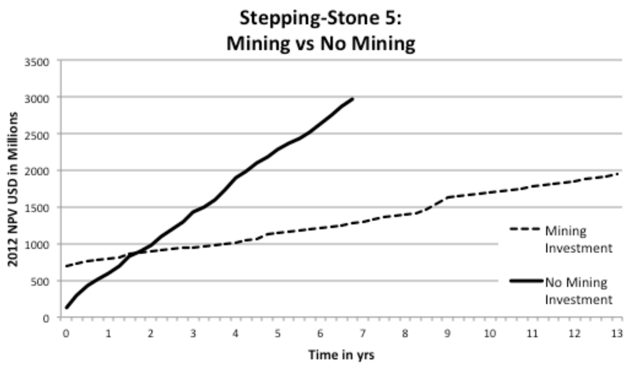

Fig. 2. Importance of Mining & Manufacturing for Stepping-Stone 5

C. *Launch Costs*

Another area of discussion is the modification of launch costs. Throughout stepping-stones 3 and 4, there is an effective reduction in launch cost as the frequency of flights increases.

The adjustment of this launch cost index sheds light onto the importance of minimizing launch costs on establishing a presence into space. For instance, by assuming a constant \$1000/lb launch cost and ignoring the benefit of higher frequency of flights on the launch cost index, a pessimistic value of the investment required in terms of launch cost is obtained. Likewise, if a technological breakthrough was to occur, and launch costs were reduced to \$1/lb, an optimistic value is obtained. Depicted in Fig. 3 is this comparison of launch costs.

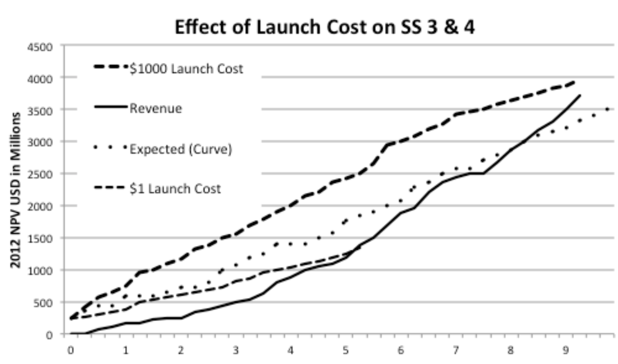

Fig. 3. Potential Investment by Launch Cost Index

VII. Recommendations

This tool can provide companies in high altitude tourism, debris collection, LEO habitation, and space tourism with insight towards whether or not to invest, how much to invest, and the price of commodities that will yield an ROI by a specified number of years.

The single-string design addresses each obstacle preventing the development of the space market. The catalyst for interest is high altitude tourism, debris collection reverses the declining conditions of LEO, and launch costs are reduced through developing a consistent demand for launches to LEO habitats, the LEO hub, and the Moon base.

VIII. Future Work

One of the largest obstacles faced during the project was the lack of publicly-available data regarding mission plans, direct & indirect costs, and performance parameters such as MTBF and lifespan. To improve the ROI calculations, there is a need to organize data in a central repository.

This project focused on establishing the top-level stepping-stones to achieve a permanent lunar habitat; individual projects could be completed on the details of each individual stepping-stone. This would provide more insight with a lower-level view of when and how capabilities should be developed.

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