

Estimation of a Moon Colonization Plan

Summary

As Earth's ecosystem approaches critical fragility, the concept of lunar colonization has evolved from theoretical science fiction into a pressing engineering imperative. This study presents a comprehensive mathematical framework for evaluating the logistical feasibility of establishing and sustaining a colony of 100,000 settlers on the Moon. We decompose the colonization process into two temporal domains—the Construction Phase and the Maintenance Phase—and optimize three competing objectives: financial cost, project duration, and environmental impact.

In the Construction Phase, we develop a multi-objective optimization model to manage transportation. The model evaluates trade-offs between two primary transport vectors: Space Elevators, characterized by high sustainability but fixed capacity, and rockets, characterized by high speed but prohibitive costs and emissions. By employing a weighted scoring system that integrates cost (S_C), time (S_T), and environmental impact (S_E), we simulate various logistical strategies.

Our simulations reveal that a hybrid approach is optimal. Crucially, our sensitivity analysis shows that In-Situ Resource Utilization rate (ISRU), denoted as α , is the decisive variable for project viability. With $\alpha \rightarrow 0$ (total Earth dependence), the construction timeline balloons to over 150 years; conversely, a high-ISRU scenario ($\alpha \approx 0.9$) makes a two-decade time limit achievable.

In the Maintenance Phase, the study shifts focus to the annual resource flows required to sustain a population of 100,000. We construct metabolic and industrial sub-models to estimate the consumption of water, food, fuel, and maintenance materials, assuming high-efficiency closed-loop recycling (98.5% water recovery) and local oxygen production. The model determines that, despite high self-sufficiency, the colony requires an annual import of approximately 4.6×10^5 tons of Earth-sourced materials—primarily Nitrogen for atmospheric buffering, Hydrogen, fine chemicals, and specialized repair components.

Logistically, this maintenance demand is well within the operational capacity of the Space Elevator system established in the first phase. We estimate the annual recurring transportation cost to be approximately 2.3×10^{11} USD. This indicates that once construction is complete, the financial burden of sustaining the colony drops substantially, provided that strict recycling protocols and local manufacturing are maintained.

Ultimately, this report concludes that the colonization of the Moon is logistically feasible within a near-future timeframe, but contingent upon two technological prerequisites: the successful deployment of a reliable Space Elevator system and the development of mature ISRU technologies to minimize mass transfer from Earth. The proposed models offer a robust foundation for future planning, demonstrating that a balance among speed, cost, and ecological stewardship is achievable.

Keywords: lunar colonization, ISRU, multi-objective optimization, Earth-Moon logistics, closed-loop recycling, carbon emissions

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1. Introduction

1.1. Background

With Earth's ecosystem becoming increasingly fragile, the prospect of lunar colonization has moved from science fiction to a potential near-future reality. This essay evaluates optimal strategies for transporting 100,000 settlers to the Moon. We analyze the project in two distinct phases—construction and maintenance—developing two models to estimate the time, financial cost, and environmental impact of various methodologies.

1.2. Literature Review

While extraterrestrial habitation has long been a staple of science fiction, the concept has recently transitioned into serious technical discourse. In 2016, SpaceX CEO Elon Musk formalized this ambition with his presentation 'Making Humans a Multi-Planetary Species' at the 67th International Astronautical Congress. [1]

This commercial drive is underpinned by earlier academic research. Notably, a 2013 study by Philip T. Metzger et al. in the Journal of Aerospace Engineering proposed a 'bootstrapping' strategy. They argued that deploying self-replicating robotic systems to utilize lunar resources is the most viable path toward sustainable colonization. [2]

1.3. Restatement of the Problem

We separate the problem into two stages, and for each stage, we build a model to estimate cost, time, and environmental impact. The two stages are:

1. Construction of the colony;
2. Maintenance of the colony;

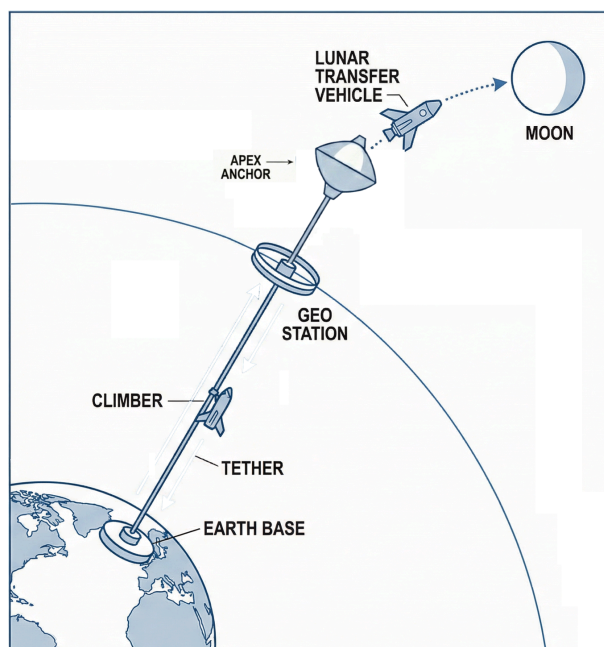


Figure 1: The model for space elevator system.

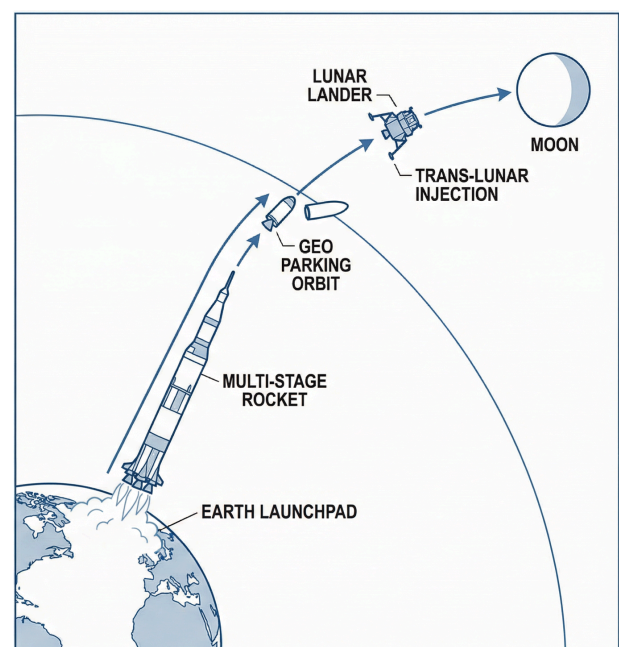


Figure 2: The model for the rocket launching.

Construction Phase

Our objective is to transport a huge amount of materials to the Moon. The launch mission comprises two stages: the first is Earth to the Apex Anchor, and the second is from the Apex Anchor to the lunar surface. However, the elevator system is limited to the Earth-to-Apex segment. As the figures show, we must use rockets to transfer cargo from the Apex Anchor to the Moon. Therefore,

in this phase, we build a multi-objective optimization model to determine the optimal frequency of rocket launches that balances time efficiency, cost control, and environmental impact.

Maintenance Phase

During operations, we must account for water and food supplies, alongside routine repairs. Notably, not all lunar consumables require Earth-based sourcing—a human-engineered ecosystem could support energy production on the Moon. Consequently, in Stage 2, we identify and quantify essential resources that must be imported from Earth.

2. Construction Phase

2.1. Assumptions

Modeling the project requires navigating significant real-world complexities. To construct a workable model, we have streamlined the parameters by excluding minor external factors.

- **Deterministic Baseline:** The core model assumes ideal operational conditions with 100% success rates for launches and transfers. Stochastic factors, such as launch failures, weather delays, or mechanical breakdowns, are excluded from the initial optimization but will be discussed in the Sensitivity Analysis.
- **ISRU Application:** Some construction materials can be sourced on the Moon, so not all items must be imported from Earth. [3], [4]
- **Integrated Overhead Costs:** Human resource expenses (wages, life support for logistics staff) are assumed to be implicitly included in the fixed annual maintenance fees (m_1) and launch operation costs. We do not model labor consumption as a separate variable.
- **Homogeneous Ground Infrastructure:** We ignore domestic transportation costs (from factories to launch sites) and assume all Earth-based launch pads are identical in terms of capability, cost, and geographical efficiency.
- **Atmospheric-Only Environmental Impact:** Environmental costs are calculated solely based on emissions within Earth's atmosphere. Rocket emissions generated during the transit from the Apex Anchor to the Moon (in the vacuum of space) are assumed to have zero environmental penalty. [5]
- **Apex Anchor Storage Ability:** The Apex Anchor has sufficient storage capacity to buffer all incoming materials from the elevators before redistribution via rockets to the Moon. Thus, no storage constraints are modeled at this node.
- **Moon Construction Efficiency:** The efficiency of construction activities on the Moon is assumed to be equivalent to Earth-based operations. We do not model any productivity differentials due to lunar gravity, radiation, or other environmental factors.

2.2. Model I Overview

Preliminary analysis indicates that space elevators outperform rockets in both cost control and environmental sustainability [6], and our later estimates support this conclusion. Therefore, their utilization should be maximized. However, rockets offer superior payload capacity, which is essential for accelerating the overall project timeline. Consequently, our primary objective is to determine the optimal frequency of rocket deployments to balance time efficiency, cost-effectiveness, and environmental impact.

The central optimization challenge involves conflicting constraints: a high frequency of rocket launches risks overloading launch pads, straining ground transportation, escalating costs, and generating substantial greenhouse gas emissions. Conversely, an overly conservative launch

schedule would excessively prolong construction. Our model aims to identify the optimal trade-off among time, cost, and environmental factors.

Furthermore, to reduce total costs, we propose that not all materials need to be transported from Earth. A significant portion of construction materials can be sourced directly from the Moon, substantially reducing both the construction timeline and expenditures. [3], [4]

2.3. Notation

Based on these assumptions and overview, we proceed to build the model. The notation and symbols used in the formulation are defined in the table below.

Symbol	Description	Unit	Range
x_t^{EA}	the mass that an elevator lifts in a year from the Earth to Apex Anchor	$\text{ton} \cdot \text{year}^{-1}$	$\mathbb{R}^*$
x_t^{AM}	the mass that was sent to the Moon from Apex Anchor in a year	ton	$\mathbb{R}^*$
n_t^{AM}	the number of spacecraft trips from Apex Anchor to the Moon	times	$\mathbb{Z}^*$
I_t	the mass that is stored in Apex Anchor in year t	ton	$\mathbb{R}^*$
y_t	the mass of materials that has arrived on the Moon	ton	$\mathbb{R}^*$
M_{total}	the mass of all the material needed	ton	10^8
C	the mass that each elevator can lift annually	$\text{ton} \cdot \text{year}^{-1}$	1.79×10^5
m_1	annual elevator maintenance fee	$\$ \cdot \text{year}^{-1}$	$\mathbb{R}^*$
m_2	cost for lifting cargo	$\$ \cdot \text{ton}^{-1}$	$\mathbb{R}^*$
m_{AM}^{ton}	the cost for transferring cargo from Apex Anchor to the Moon	$\$ \cdot \text{ton}^{-1}$	$\mathbb{R}^*$
m_{AM}^{launch}	the cost for each launch from Apex Anchor to the Moon	$\$ \cdot \text{times}^{-1}$	$\mathbb{R}^*$
m_{EM}^{ton}	the average cost for sending 1 ton of cargo from Earth to the Moon	$\$ \cdot \text{ton}^{-1}$	$\mathbb{R}^*$
m_{EM}^{launch}	the baseline cost for one launch	$\$ \cdot \text{times}^{-1}$	$\mathbb{R}^*$
g_R	climate-change impact per launch	$t\text{CO}_2e \cdot \text{times}^{-1}$	$\mathbb{R}^*$
U_R	maximum times that a single launch pad can launch a rocket annually	times	$\mathbb{N}^*$
τ_{dead}	the maximum duration of the construction	year	$\mathbb{N}^*$
t	duration of the construction	year	$\mathbb{N}^*$
L	Load of the rocket from the Earth to the Moon	ton	$L_{\min} \leq L \leq L_{\max},$ $L_{\min} = 100, L_{\max} = 150$

α	fraction of construction mass supplied via ISRU; the larger α is, the less materials must be imported	N/A	(0, 1)
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2.4. Model Details

2.4.1. Sub-Model I: Comparison

There are generally three strategies for sending all cargo to the Moon. As stated in the problem, a total of $M_{\text{total}} = 10^8$ cargo needs to be sent to the Moon. In this model, we assume that none of the required cargo can be replaced by lunar resources and must be imported from Earth. In other words, we assume $\alpha = 0$, and obtain:

- Plan A: use rockets alone:

$$t_a = \frac{M_{\text{total}}}{10 \times U_R \cdot L}. \quad (1)$$

$$C_a = t_a \cdot 10 \times U_R \cdot (m_{\text{AM}}^{\text{launch}} + m_{\text{AM}}^{\text{ton}} \cdot L) = \frac{M_{\text{total}}}{L} \cdot (m_{\text{AM}}^{\text{launch}} + m_{\text{AM}}^{\text{ton}} \cdot L). \quad (2)$$

$$E_a = 10 \times t_a \cdot U_R \cdot g_R. \quad (3)$$

- Plan B: use elevator system alone

$$t_b = \frac{M_{\text{total}}}{3 \times x_t^{\text{EA}}}. \quad (4)$$

$$C_b = 3 \times m_1 \cdot t_b + m_2 \cdot M_{\text{total}} + \frac{M_{\text{total}}}{L} \cdot m_{\text{AM}}^{\text{launch}} + M_{\text{total}} \cdot m_{\text{AM}}^{\text{ton}}. \quad (5)$$

$$E_B = 0. \quad (6)$$

- Plan C: a linear combination of the previous two plans. In this plan, the total cost, time consumption and carbon emission are some where between the value of the previous two.

We estimated the parameters:

Symbol	Value	Symbol	Value	Symbol	Value
M_{total}	1×10^8	U_R	3.6×10^2 [7]	m_1	4×10^8 [6], [8]
$m_{\text{AM}}^{\text{ton}}$	1×10^4 [6], [8]	$m_{\text{AM}}^{\text{launch}}$	1×10^6 [6], [8]	$m_{\text{EM}}^{\text{ton}}$	5×10^6 [9]
$m_{\text{EM}}^{\text{launch}}$	5×10^7 [9]	g_R	3×10^3 [10]	L	1.5×10^2

We also use the interior equations of these parameters:

$$3 \times x_t^{\text{EA}} = C = 1.79 \times 10^5. \quad (7)$$

Using the equations above, we get the result:(Plan C is a compromise of Plan A and Plan B)

Symbol	Value	Symbol	Value
t_a	185.2	t_b	186.2
E_a	1.94×10^9	E_b	0
C_a	5.01×10^{14}	C_b	5.17×10^{13}

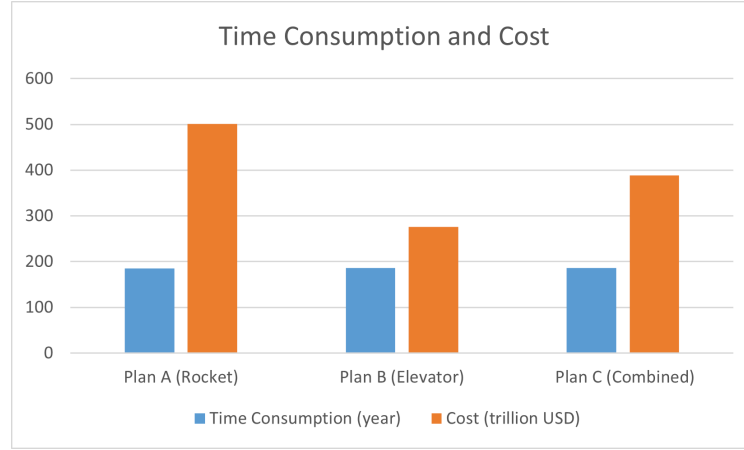


Figure 3: Comparison of the three possible plans

Conclusion

It is clear that using the elevator system is far more cost-saving while generating almost no greenhouse gases. Thus, we rely heavily on the elevator system, while rocket launches serve as a strategy to supplement the limited capacity of the three space elevators.

With this rough estimate, we find that space elevators outperform rocket launches in terms of both cost control and environmental sustainability. Therefore, space elevators should be utilized as extensively as possible. The advantage of rocket launches lies in their payload capacity, which can accelerate the overall construction timeline. Thus, our primary goal is to determine how frequently rockets should be deployed within a specified timeframe to optimize time efficiency, cost control, and environmental outcomes for the project.

2.4.2. Sub-Model II: Construction

2.4.2.1. Constraints

To build this model, the parameters should be given a range, and each parameter may interact with one another. In this section, we use equations to express the relations of some of the parameters mentioned above.

- The mass that the Moon base receives each year equals the sum of rocket cargo and elevator-delivered cargo. The cumulative mass received must be sufficient to complete construction, so we obtain the following equations¹:

$$y_t = x_t^{\text{EM}} + x_t^{\text{AM}}. \quad (8)$$

$$\sum_{t \in \mathcal{T}} y_t \geq (1 - \alpha) \cdot M_{\text{total}}. \quad (9)$$

- The materials stored in Apex Anchor cannot be a negative number:

$$I_1 = 0, I_t = I_{t-1} + x_t^{\text{EA}} - x_t^{\text{AM}} \geq 0. \quad (10)$$

- The constraint for the elevator system:

$$x_t^{\text{EA}} \leq 3C. \quad (11)$$

- The constraint for rocket launches:

$$n_t^{\text{EM}} \leq 10U_R, x_t^{\text{EM}} \leq n_t^{\text{EM}} \cdot L, x_t^{\text{AM}} \leq n_t^{\text{AM}} \cdot L. \quad (12)$$

¹In the symbol x_t^{EA} , the upper index E means Earth, and A means Apex Anchor. The naming of other symbols follows similar rules; for example, 'M' refers to the Moon.

2.4.2.2. Score Rating system

To evaluate the plans and identify the best one, we build a score-rating model. First, we define t as the duration of construction, and let τ be the minimum value of t that satisfies the construction requirement². So we get

$$\tau = \min \left\{ t \in \mathcal{T} \mid \sum_{k=1}^t y_k \geq M_{\text{total}} \right\}. \quad (13)$$

Then, we calculate the total cost C_{total} . Because the duration is τ years, we can sum the cost across years:

$$C_{\text{total}} = \sum_{t=1}^{\tau} (3m_1 + m_2 x_t^{\text{EA}} + m_{\text{AM}}^{\text{ton}} x_t^{\text{AM}} + m_{\text{AM}}^{\text{launch}} n_t^{\text{AM}} + m_{\text{EM}}^{\text{ton}} x_t^{\text{EM}} + m_{\text{EM}}^{\text{launch}} n_t^{\text{EM}}). \quad (14)$$

We also account for environmental impact. To simplify the problem, we assume that only rockets generate pollution or greenhouse gases, because spacecraft travel in space and emissions released into the vacuum do not affect Earth's atmosphere. Using the symbol E_{CO_2} to describe CO_2 emissions, we obtain

$$E_{\text{CO}_2} = \sum_{t=1}^{\tau} g_R n_t^{\text{EM}}. \quad (15)$$

We use $\mathcal{P}$ to refer to the set of all the plans.

Symbol	Expression	Symbol	Expression
$C_{\min}$	$\min_{p \in \mathcal{P}} C_{\text{total}(p)}$	$C_{\max}$	$\max_{p \in \mathcal{P}} C_{\text{total}(p)}$
$T_{\min}$	$\min_{p \in \mathcal{P}} T_{\text{total}(p)}$	$T_{\max}$	$\max_{p \in \mathcal{P}} T_{\text{total}(p)}$
$E_{\min}$	$\min_{p \in \mathcal{P}} E_{\text{total}(p)}$	$E_{\max}$	$\max_{p \in \mathcal{P}} E_{\text{total}(p)}$

After normalizing the data, we can process it appropriately to avoid errors caused by differences in units. The specific steps for normalization are as follows. We use S_C to describe a plan's cost score, while S_T refers to its time score and S_E reflects its environmental impact. To normalize the metrics, let

$$S_C = \frac{C_{\max} - C_{\text{total}}}{C_{\max} - C_{\min}}, S_T = \frac{T_{\max} - T_{\text{total}}}{T_{\max} - T_{\min}}, S_E = \frac{E_{\max} - E_{\text{CO}_2}}{E_{\max} - E_{\min}}, S_C, S_T, S_E \in [0, 1]. \quad (16)$$

However, we do not assume these three scores are equally important. Therefore, we apply a weighted averaging process, where the weight assigned to each score varies and can be adjusted according to practical needs. In this model, we let w_C, w_T, w_E

$$S = (S_C^{w_C} S_T^{w_T} S_E^{w_E})^{\frac{1}{w_C + w_T + w_E}} \in (0, 1). \quad (17)$$

In this model, we let $w_C = 4, w_T = 4, w_E = 2$, and we built a Python project to compute the best plan. We also estimate the parameter values:³

Symbol	Value	Symbol	Value	Symbol	Value
M_{total}	1×10^8	U_R	3.6×10^2 [7]	m_1	4×10^8 [6], [8]
m_2	5×10^5 [6], [8]	$m_{\text{AM}}^{\text{ton}}$	1×10^4 [6], [8]	$m_{\text{AM}}^{\text{launch}}$	1×10^6 [6], [8]

²Though this equation seems useless and obvious, it is how we determine that the project is finished in the python project we built. The source code can be found in the Appendices section.

³The references of these parameters can be found in the References section, just click the links after each value.

$m_{\text{EM}}^{\text{ton}}$	5×10^6 [9]	$m_{\text{EM}}^{\text{launch}}$	5×10^7 [9]	g_R	3×10^3 [10]
τ_{dead}	40	C	1.79×10^5	L	1.5×10^2

This is what we get:

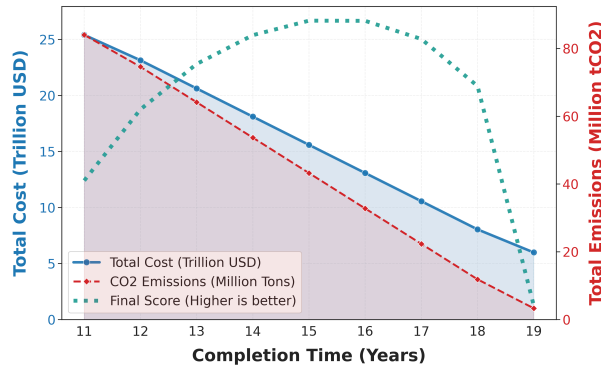


Figure 4: When $\alpha = 0.9$, total cost and total emission changes as completion year increases. [4]

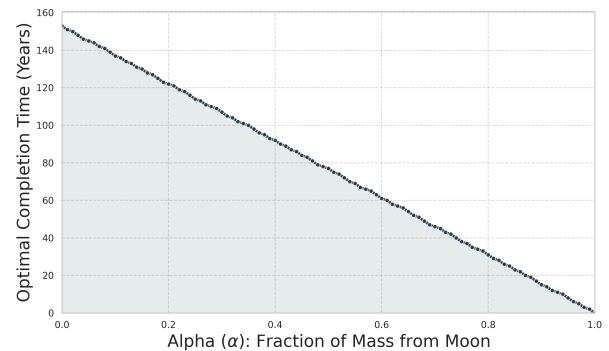


Figure 5: Optimal completion time decreases as α increases

Figure 4 illustrates the multi-objective optimization trade-offs occurring when the lunar resource utilization rate (α) is fixed at 0.9. The chart employs a dual y-axis to contrast financial and ecological costs against the project's timeline. There is a clear inverse linear relationship between the completion time and both cost and emissions; as the project duration extends from 11 to 19 years, the Total Cost (solid blue line) drops significantly from over 25 trillion USD to approximately 6 trillion USD. Similarly, CO₂ Emissions (dashed red line) decline precipitously from over 80 million tons to near-zero levels as the timeline lengthens, suggesting that a slower pace allows for more efficient, less carbon-intensive operations. However, the “Final Score” (dotted green line), which aggregates these factors, follows a parabolic trajectory. It rises initially as costs fall but peaks between years 14 and 16 before declining sharply after year 17. This indicates that while extending the timeline saves money and the environment, there is a limit to this benefit; beyond the optimal window of 14-16 years, the penalties associated with delay outweigh the marginal gains in cost and emission reductions.

Figure 5 highlights the critical influence of resource sourcing on the project's temporal efficiency. The plot tracks the “Optimal Completion Time” against α , which represents the fraction of total construction mass derived from the Moon. The data reveals a strong negative correlation: as the reliance on lunar resources increases (moving from 0.0 to 1.0 on the x-axis), the time required to optimally complete the project decreases in a near-linear fashion. When the project relies entirely on Earth imports ($\alpha = 0$), the optimal timeline exceeds 150 years, reflecting the extreme logistical difficulty of transporting mass from Earth. Conversely, as α approaches 1.0, signifying full utilization of lunar resources, the optimal completion time drops to nearly zero. This trend underscores that maximizing in-situ resource utilization is the primary driver for accelerating the project timeline.

2.5. Conclusion for Construction Phase

Our analysis concludes that the optimal construction strategy requires a hybrid logistical approach, balancing the speed of rockets with the sustainability of space elevators. The scoring model identifies a distinct utility peak at a duration of 14 to 16 years, preventing both the prohibitive costs of a rushed timeline and the inefficiency of prolonged delays. This “sweet spot” allows the

elevator system to handle the majority of the payload, restricting high-emission rocket launches to essential, time-sensitive support roles.

Furthermore, the model proves that In-Situ Resource Utilization (α) is the definitive variable for project viability. Without significant local manufacturing, the construction timeline balloons to about 150 years, rendering the project impractical. Thus, technological investment in lunar mining is a prerequisite for completion. With the construction parameters optimized for a high-ISRU scenario, we proceed to the Maintenance Phase to model the recurring resource flows required to sustain the colony.

2.6. Flaws and Improvements

2.6.1. Flaws

Although many aspects have been considered, our model still has limitations. First, some parameter estimates require further scientific validation. In our model, these values are based on limited literature, which means they may be imprecise and may not reflect the most current research. Such parameters include α and U_R .

Furthermore, our model does not explicitly incorporate technological progress. This omission could compromise accuracy, given that the mission is scheduled in 2050 – a horizon where substantial technological change is plausible. To partially address this, we assume that technological improvements reduce the cost of sending cargo to space relative to current levels; however, such statistics are only rough estimates based on public sources.

2.6.2. Improvements

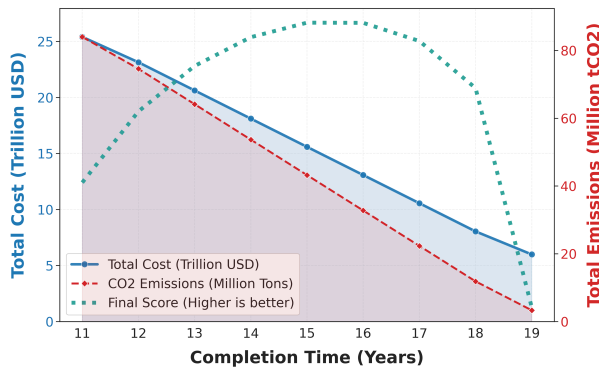


Figure 6: ideal situation

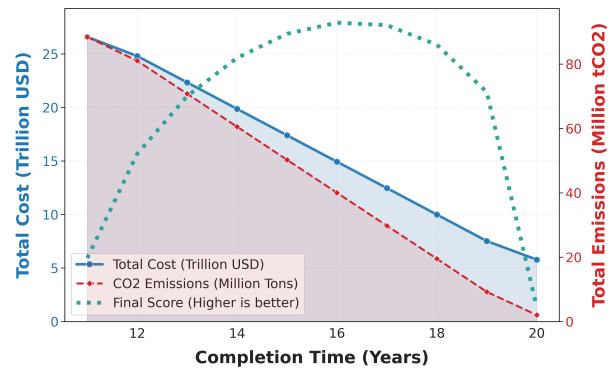


Figure 7: Each process faces 2% failures

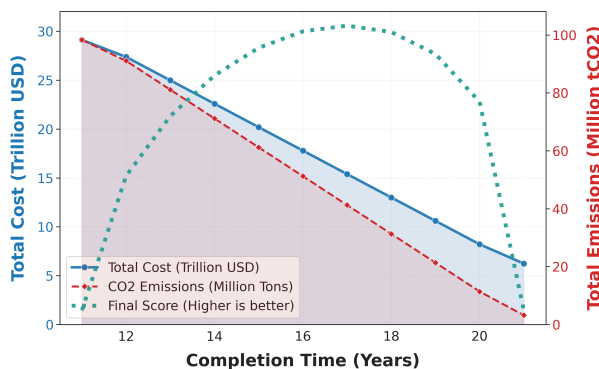


Figure 8: Each process faces 5% failures

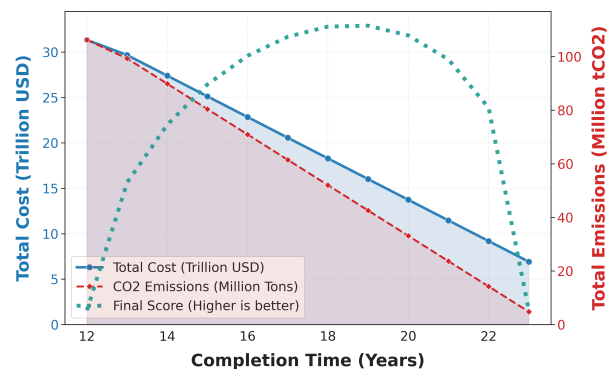


Figure 9: Each process faces 10% failures

The model was built on “perfect condition”, which means no delays or failure of launches, no weather influence on the elevator etc. are considered. Thus, we changed the model a little bit to take

these factors into consideration. We assume that each process may face some failures, and draw the diagrams showing the failure rate influence on the 3 factors: time, cost and environmental influence. Let β be the failure rate. In the above images, each refers to the situation that $\beta = 0, 2\%, 5\%, 10\%$.

According to these diagrams, using this scoring system, the duration of construction is not strongly affected as the failure rate varies between 0% and 10%. However, higher failure rates increase the total cost. These diagrams suggest that the score-rating model is relatively stable. Thus, we believe it can be used in practice, as failure rates in space missions are typically below 10%.

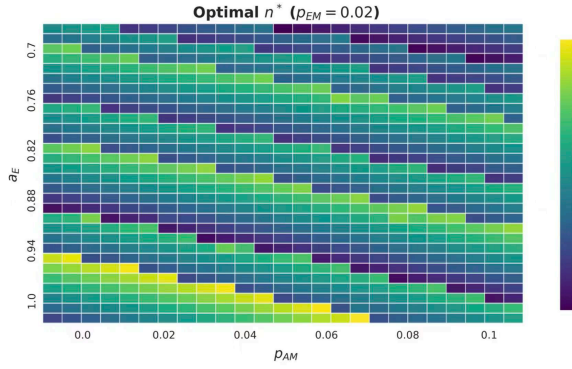


Figure 10: the optimal launching frequency of rockets when $p_{EM} = 2\%$

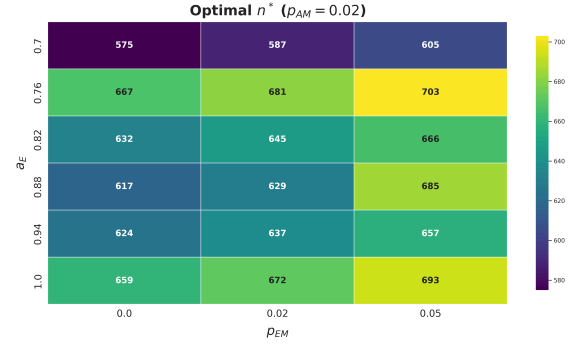


Figure 11: the optimal launching frequency of rockets when $p_{AM} = 2\%$

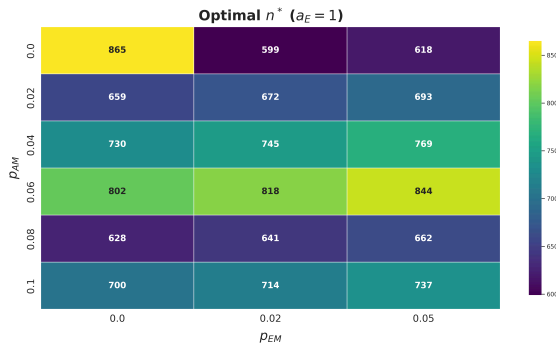


Figure 12: the optimal launching frequency of rockets when $a_E = 100\%$

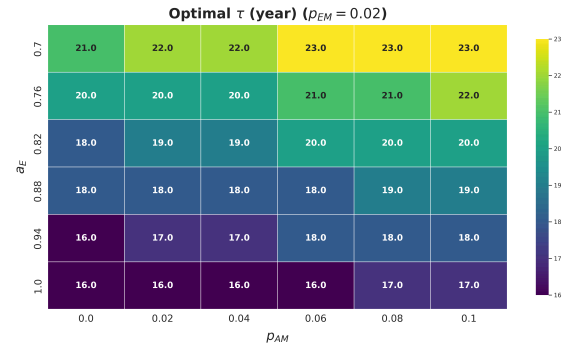


Figure 13: the optimal duration of the whole mission when $p_{EM} = 2\%$

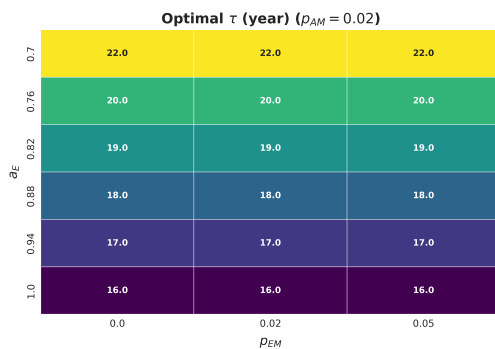


Figure 14: the optimal duration of the whole mission when $p_{AM} = 2\%$

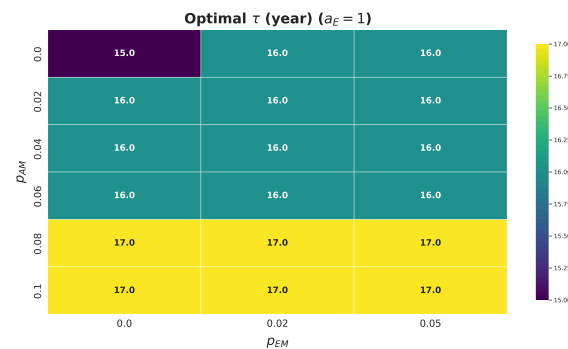


Figure 15: the optimal duration of the whole mission when $a_E = 100\%$

To do sensitivity analysis, we made the following diagrams, showing the influence of failure rates on the 3 factors: time, cost and environmental influence.⁴

⁴ p_{EM} and p_{AM} refers to the failure rate of rocket launching from the Earth to the Moon or from the Apex Anchor to the Moon base. a_E refers to the failure rate of the elevator system and n^* means how many launches need to be operated.

The first three figures (Figure 10, 11, 12) show the optimal launching frequency of rockets when different failure rates are given. The last three figures (Figure 13, 14, 15) show the optimal duration of the whole mission when different failure rates are given. From these diagrams, we can see that:

1. When the stability of the rocket and elevator systems decreases, people tend to launch rockets more frequently to compensate for failures and ensure the mission can be completed on time. However, when the failure rate is too high, people tend to launch rockets less frequently to save money and accept modest schedule delays.
2. According to Figure 10 and 13, with p_{EM} fixed, when $a_E + p_{EM} = \text{constant}$, the optimal launching frequency of rockets will not change too much, and the optimal duration of the whole mission will not change too much either.
3. According to Figure 14, p_{EM} does not have too much influence on the optimal duration of the whole mission compared to a_E . This is because the failure rate for rockets is quite low, and thus will not delay the mission drastically.
4. We also observe that the lower p_{AM} and p_{EM} are, the more reliable rocket launches become, so the model tends to use rockets more frequently to speed up the mission.

The sensitivity analysis demonstrates that the Space Elevator's reliability (a_E) is the single most decisive factor for the project's success. A decrease in elevator availability leads to a drastic increase in project duration (up to 43%) and forces a costly reliance on backup rocket launches. Conversely, the system displays high resilience to rocket launch failure rates (p_{AM} and p_{EM}), suggesting that occasional launch failures are manageable operational costs rather than catastrophic schedule risks.

3. Maintenance Phase

After the construction of the Moon base, we still need to consider how to transport living necessities to the Moon. The transportation model from the construction phase can still be used by changing the parameter M_{total} to the annual import mass. Thus, our core goal is to estimate how much must be imported from Earth.

3.1. Assumptions

The composition of the supplies differs significantly from terrestrial needs. For instance, conventional vehicles are unnecessary. Our primary objective is to estimate the total mass of essential cargo. To simplify the model while maintaining accuracy, we establish the following assumptions:

- **Categorization of Supplies:** We classify all imports into four core categories: Water, Food (including medicine and biological consumables), Fuels, and **maintenance materials** (for base repairs). Minor items, such as clothing, are considered negligible or are integrated into these categories. [11]
- **High-Efficiency Recycling:** The Moon Colony operates an advanced water reclamation system capable of purifying and recycling the vast majority of wastewater. [11]
- **Routine Maintenance Only:** We assume a stable operational state where no catastrophic disasters occur. Consequently, the mass estimation for "Maintenance Materials" covers only routine repairs and part replacements, rather than large-scale reconstruction of the infrastructure.
- **Standardized Metabolic Unit:** The population is modeled as homogeneous "average adults" in terms of metabolic consumption. Variations in age, gender, and body mass are averaged out to a single daily per-capita consumption rate for water, calories, and oxygen.
- **Selective Resource Dependency:** We assume the Moon Colony has achieved self-sufficiency in many aspects of production. Therefore, only critical resources that cannot be manufactured

in-situ, or would require excessive water and other inputs to produce, are considered for import from Earth. We find that the Moon is rich in metals like iron and aluminum, so we do not consider importing these materials from Earth. [12]

- **Technological Stasis:** The efficiency of life support systems, recycling rates, and propulsion technologies remains constant throughout the simulation period (2050 onwards). We do not factor in speculative technological singularities that could drastically alter consumption rates.

3.2. Estimation Model

3.2.1. Sub-model I: Water Estimation

3.2.1.1. Description

Water consumption primarily falls into three categories: domestic use, agricultural irrigation, and industrial applications. Currently, the water recycling rate for domestic use on space stations has reached 98%. Therefore, we consider it reasonable to set the recycling rate at 98.5% in the coming decades. In a lunar colony, agricultural and industrial water demand is unlikely to exceed current per-capita usage on Earth. Thus, estimating these needs based on Earth's current per-capita consumption is more than sufficient. We slightly scale back this estimate, as the Moon will not host the same breadth of industrial categories as Earth.

To imitate conditions on the Moon, we reviewed the ISS (International Space Station) water recovery and management system and based our estimates on it. Figure 16 shows how water is reused through multiple steps on the ISS.

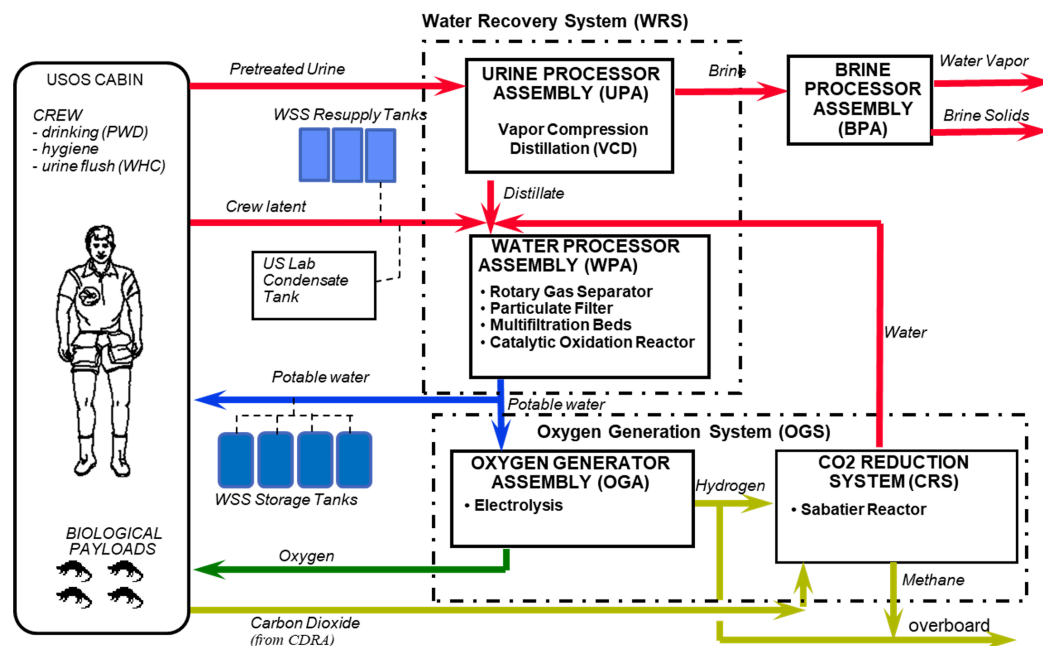


Figure 16: Water Recovery and Management Architecture for the ISS US Segment [13]

3.2.1.2. Notations

Symbol	Description	Unit	Range
N	population size	person	1×10^5
W_L	the amount of water a person needs for domestic use	$\text{kg} \cdot (\text{person} \cdot \text{day})^{-1}$	$W_L \in [3, 5]$

W_I	industrial and irrigation water needed per person per day	$\text{ton} \cdot (\text{person} \cdot \text{day})^{-1}$	$W_I \in [0.8, 1]$
$\text{Sum}_{\text{total}}$	total water needed on the Moon	$\text{ton} \cdot \text{year}^{-1}$	$\mathbb{R}^*$
$\text{Sum}_{\text{import}}$	total water that must be imported	$\text{ton} \cdot \text{year}^{-1}$	$\mathbb{R}^*$
α_L	recycle rate for domestic needs	N/A	$\alpha_L \in (0, 1)$
α_I	recycle rate for industrial and irrigation needs	N/A	$\alpha_I \in (0, 1)$

Model details

$$\text{Sum}_{\text{total}} = N \cdot (W_L + W_I), \text{Sum}_{\text{import}} = N \cdot (W_L \cdot \alpha_L + W_I \cdot \alpha_I). \quad (18)$$

Because most water can be recycled, according to the study published online [14], we estimate $\alpha_L = \alpha_I = 99\%$. Then we obtain

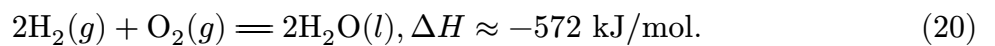
$$\text{Sum}_{\text{import}} = 10^5 \cdot 0.9 \cdot 365 \cdot 1\% = 3.3 \cdot 10^5 (\text{ton} / \text{year}) \quad (19)$$

3.2.2. Sub-model II: Food and Industrial Estimation

3.2.2.1. Description

Given the diversity of food types, conducting statistical estimates directly on food is challenging. Therefore, we shift our focus to the import requirements for key chemical elements needed by humans. We note that the Moon itself can supply resources such as iron, aluminum, titanium, and water, but it lacks carbon, hydrogen, and nitrogen. [11] As a result, the Moon can provide many raw materials for metal products. Thus, the key issues lie in delivering nitrogen to maintain atmospheric pressure, as well as transporting fine chemical products such as fertilizers and pharmaceuticals.

Fuel and other energy carriers can be supplied through methods with minimal mass requirements, such as controlled nuclear fusion and hydrogen combustion. With a rough estimate, this mass is minor compared to food and water supply requirements. Moreover, sending liquid O_2 and H_2 to the Moon can provide both water and energy:⁵



3.2.2.2. Notations

Symbol	Description	Unit	Value
C	requirement for carbon	ton	$\mathbb{R}^*$
H	requirement for Hydrogen	ton	$\mathbb{R}^*$
N	requirement for Nitrogen	ton	$\mathbb{R}^*$
F	fine chemical products that are too hard to produce on the Moon	ton	$\mathbb{R}^*$
V	space for a person to live	m^3	$V \in [50, 100]$
p_{N_2}	N_2 pressure in the Moon base	kpa	50

⁵In fact, sending elements is better than sending compound in most occasions, as synthesis reactions are usually exothermic. For example, $\text{N}_2(g) + 3\text{H}_2(g) = 2\text{NH}_3(g), \Delta H \approx -92.4 \text{ kJ} / \text{mol}$.

m_{N_2}	weight of N_2 needed in the base	ton	$\mathbb{R}^*$
T	temperature in the base	K	295

3.2.2.3. Model detail

• N_2 estimation

Let us assume that an adult needs 2,500 kcal per day, which implies a diet of roughly 300 g carbohydrate, 70 g fat, and 90 g protein. [15] For the N_2 gas estimate, using the ideal gas law $pV = nRT$, we obtain

$$m_{N_2} = \frac{p_{N_2} V}{RT} M_{N_2} = 0.056(\text{ton} / \text{person}) \quad (21)$$

Thus, the total Nitrogen required is $0.056 \times 10^5 = 5.6 \times 10^3$ tons. This calculation effectively assumes that N_2 is replenished annually in the base; in reality, N_2 does not need to be replaced nearly that frequently, so our estimate should comfortably satisfy actual needs on the Moon base.

• Carbon and fine chemical product estimation

Carbon can be cycled on the Moon, as can most other elements. Thus, we shift our focus to fine chemical products. This category includes medicines and detergents. We estimate that 0.01 to 0.05 tons of fine chemical products are needed per person per year. We use the midpoint: $F = N \times 0.03 = 3 \times 10^3(\text{ton})$. Our team members also estimated the carbon requirement, and the results are of the same order of magnitude; thus, we use the average estimate: $C = 2 \times 10^3(\text{ton})$.

• Repairing estimation

Given that no major disasters occur, we believe that routine repair work will not require substantial imported cargo from Earth. In addition, the water and oxygen in the base are contained within engineered systems, so iron should rust slowly. Although we lack precise data, we found news reports on routine repairs of the International Space Station and estimate that about $\mu = 1\%$ to 3% of the base needs to be replaced each year. However, not all replacement materials must be imported. As ISRU technology develops, we estimate that only about 10% of replacement materials need to be shipped from Earth. $M_{\text{repair}} = M_{\text{total}} \cdot 10\% \cdot \mu \approx 10^5 \text{ ton}$. [11]

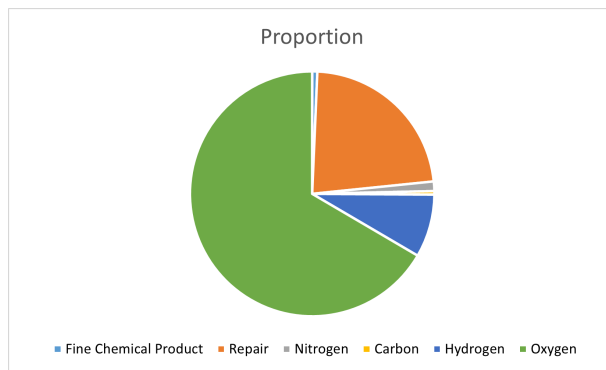


Figure 17: Proportion of each kind of resources needed to be imported from the Earth⁶

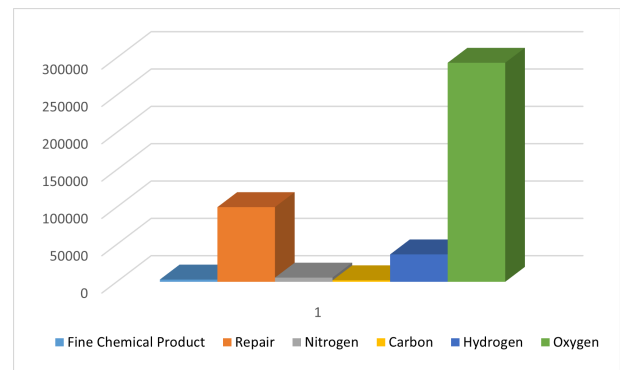


Figure 18: The weight of each kind of resources needed to be imported from the Earth

• Total amount

⁶We made estimation on the amount of water needed, and we believe the most economic way to import water is to send liquid O_2 gas and H_2 gas to the Moon, then synthesize them into water on the Moon. Thus, the mass of water is counted into the mass of hydrogen and oxygen.

We also note that most carbon is stored in biomass, so we combine the estimate of H with C , and conclude that $M_{\text{repair}} + C + N = 1.3 \times 10^5$ tons is sufficient for supplying the Moon. According to our estimates and official data, we believe that the resources the Moon base **must** import from Earth are no more than 4.6×10^5 tons per year. This mass includes not only water, but also food, fine chemical products, and repair materials, and should fully satisfy the needs of a population of 10^5 people.

3.3. Transportation model

3.3.1. Calculation

We find that the total amount of resources that must be imported from Earth is about 4.6×10^5 tons annually. We then use the model from the construction phase to estimate how to transport these resources to the Moon base. The only difference is that the value of M_{total} changes to 4.6×10^5 tons. Another constraint for using the previous model is that the time required for transportation should not be too long ($\tau_{\text{dead}} \leq 1$). Table below lists the parameters used in the transportation model from the construction phase:

Symbol	Value	Symbol	Value
M_{total}	4.6×10^5	U_R	3.6×10^2
m_1	4×10^8	m_2	5×10^5
$m_{\text{AM}}^{\text{ton}}$	1×10^4	$m_{\text{AM}}^{\text{launch}}$	1×10^6
$m_{\text{EM}}^{\text{ton}}$	5×10^6	$m_{\text{EM}}^{\text{launch}}$	5×10^7
g_R	3×10^3	τ_{dead}	1
C	1.79×10^5	L	1.5×10^2

We realize that the elevator system can fully satisfy the need of transportation, so we decide to use it alone. Then we get the following results:⁷

$$C_{\text{total}} = 3 \times m_1 \cdot \tau_{\text{dead}} + m_2 \cdot M_{\text{total}} \approx 2.3 \times 10^{11} (\text{USD}) \quad (22)$$

3.4. Conclusion

According to our estimation, the Moon base with a population of 10^5 people needs to import about 4.6×10^5 tons of resources from the Earth annually. Using the space **elevator system** alone can fully satisfy the transportation need, and the total cost is about 2.3×10^{11} USD annually.

3.5. Flaws and Improvements

3.5.1. Flaws

We have to admit that this is a rough estimate of the resources that must be imported from Earth. The main limitations are listed as follows.

We do not know exactly how much can be produced on the Moon, and we do not know how much the Moon will rely on Earth in the future. Also, we do not have precise per-capita consumption data, so we estimate based on average data on Earth. Moreover, we do not consider technological progress, which may greatly change consumption and recycling rates in the future.

⁷The GDP of the United States in 2024 is about 2.92×10^{13} USD.

3.5.2. Improvements

To improve the model, we can do more research on production capacity on the Moon and determine what percentage of resources can be produced there in the future. We can also investigate per-capita consumption in more detail and obtain more precise data. Furthermore, we can incorporate technological progress by modeling plausible improvements in future systems.

In fact, we conducted some of this research. For example, we consider controlled nuclear fusion as the main energy supply method on the Moon, which can greatly reduce the mass of fuel that must be imported from Earth. We also assume a high-efficiency recycling system to reduce water consumption. Our data are largely based on scientific research on future technology; thus, we believe our model is broadly reasonable.

4. Conclusion

This study shows that establishing and sustaining a Moon colony of 100,000 settlers is logistically feasible, but only under a tightly coupled strategy that prioritizes sustainability without sacrificing schedule.

In the Construction Phase, our multi-objective scoring model indicates that space elevators should carry the bulk of mass due to their low cost and near-zero atmospheric emissions, while rockets are best used sparingly as a time-acceleration tool; under a high-ISRU scenario (e.g. $\alpha \approx 0.9$), the overall utility peaks at an optimal completion window of roughly 14 to 16 years. Sensitivity results further demonstrate that ISRU is the decisive driver of feasibility—without substantial lunar sourcing ($\alpha \rightarrow 0$), the timeline expands beyond 150 years—while elevator reliability is a larger schedule risk than rocket failure rates.

In the Maintenance Phase, even with aggressive recycling and local oxygen production, the colony still requires on the order of 4.6×10^5 tons of annual Earth imports (primarily nitrogen buffering gas, hydrogen/volatiles, fine chemicals, and specialized spares), which can be handled by the elevator system alone at an estimated recurring transportation cost of 2.3×10^{11} USD per year.

Overall, the project is achievable in a near-future timeframe provided that robust space-elevator operations and mature ISRU capabilities are realized.

However, we doubt that this project can reduce environmental impacts to a very low level. During construction, a large number of rockets must be launched from Earth to the Moon, which will generate substantial greenhouse gas emissions. Thus, further research is needed on how to reduce environmental impacts during the construction process.

We also consider ethical issues regarding this project. For example, what if people on the Moon base feel abandoned by Earth? Will they share the same rights as their Earth counterparts, or will they regard themselves as a different society after living on the Moon for decades? Such ethical issues should be considered before the project starts.

A Letter to MCM Scientists

Dear Members of the MCM Committee,

On behalf of our team, I submit for your consideration our study, *Estimation of a Moon Colonization Plan*, which develops a quantitative framework to evaluate the logistics of establishing and sustaining a lunar colony of 100,000 settlers. Our intent is to provide MCM with a transparent, parameter-driven tool for early-phase planning and trade studies—especially those involving Earth-Moon mass transport, schedule risk, and sustainability.

We model the program in two phases. In the Construction Phase, we formulate a multi-objective optimization that balances (i) total cost, (ii) completion time, and (iii) atmospheric emissions. The model explicitly compares two transport vectors: space elevators (low recurring marginal emissions, fixed annual capacity) and rockets (high speed and flexibility, but high cost and emissions). Using a weighted scoring method that integrates these objectives, our simulations consistently favor a hybrid architecture: elevators should carry the majority of mass, while rockets are reserved for schedule acceleration and time-sensitive bottlenecks.

A central outcome is that In-Situ Resource Utilization (ISRU) is the decisive feasibility variable. Letting α denote the fraction of construction mass sourced on the Moon, we find that with $\alpha \rightarrow 0$ (full Earth dependence), the completion timeline expands to >150 years, rendering the plan effectively impractical. In contrast, with a high-ISRU scenario $\alpha \approx 0.9$, the optimal completion window peaks at 14-16 years, providing a plausible near-future pathway. Sensitivity analysis further indicates that elevator reliability is the dominant schedule risk driver; moderate rocket failure rates are comparatively manageable.

In the Maintenance Phase, we estimate annual imports under high-efficiency closed-loop operations (e.g., 98.5% water recovery and local oxygen production). Even with strong recycling, the colony still requires approximately 4.6×10^5 tons/year of Earth-sourced materials—primarily nitrogen buffering gas, hydrogen, fine chemicals (fertilizers, pharmaceuticals) and specialized spare parts. This demand is within the capacity of the elevator system, with a modeled recurring transportation cost of roughly 2.3×10^{11} USD/year.

We respectfully recommend that MCM: prioritize investment and qualification roadmaps for mature ISRU, and treat space-elevator availability and maintainability as a top-level program requirement, with rockets as a bounded supplement rather than a primary logistics backbone.

We would welcome the opportunity to provide the full model description, parameter tables, and simulation code for independent replication and extension by MCM analysts.

Thank you for reading this letter and considering our work. We look forward to your feedback and the possibility of contributing further to MCM's visionary lunar colonization efforts.

Best wishes!

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Appendices

Appendices A: Code for the Model in the Construction Phase

The code for the model in the construction phase is shown below. Using this code, we successfully worked out the optimal launching frequency of rockets needed to finish the construction within the deadline, as well as the total cost and total carbon emissions.

```
import argparse
import json
import math
from pathlib import Path

def simulate(c, n_em_year, L, year_cap):
    a_E = float(c.get("a_E", 1.0))
    p_AM = float(c.get("p_AM", 0.0))
    p_EM = float(c.get("p_EM", 0.0))
    M = float(c["M_total_ton"]) * (1 - float(c.get("alpha", 0.0)))
    elev_cap = int(c["num_elevators"]) * float(c["C_ton_per_year_per_elevator"]) *
a_E
    m1 = float(c["m_1_usd_per_year_per_elevator"]) * int(c["num_elevators"])
    m2, m3t, m3l, m4t, m4l = (
        float(c[k])
        for k in (
            "m_2_usd_per_ton",
            "m_3_tt_usd_per_ton",
            "m_3_launch_usd_per_launch",
            "m_4_tt_usd_per_ton",
            "m_4_launch_usd_per_launch",
        )
    )
    gR = float(c["g_R_tCO2_per_launch"])
    delivered = cost = 0.0
    n_em_tot = n_am_tot = 0
    for year in range(1, year_cap + 1):
        rem = M - delivered
        if rem <= 0:
            return {
                "n": n_em_year,
                "ok": True,
                "tau": year - 1,
                "C": cost,
                "E": gR * n_em_tot,
                "n_em_tot": n_em_tot,
                "n_am_tot": n_am_tot,
            }
        am_success = max(0.0, 1.0 - p_AM)
        em_success = max(0.0, 1.0 - p_EM)
        x_am = min(elev_cap, rem / am_success)
        n_am = 0 if x_am <= 0 else int(math.ceil(x_am / L))
        rem2 = max(0.0, rem - am_success * x_am)
        x_em = min(n_em_year * L, rem2 / em_success)
        n_em = 0 if x_em <= 0 else int(math.ceil(x_em / L))
        delivered += am_success * x_am + em_success * x_em
        cost += m1 + m2 * x_am + m3t * x_am + m3l * n_am + m4t * x_em + m4l * n_em
        n_em_tot += n_em
        n_am_tot += n_am
```

```

        if delivered >= M:
            return {
                "n": n_em_year,
                "ok": True,
                "tau": year,
                "C": cost,
                "E": gR * n_em_tot,
                "n_em_tot": n_em_tot,
                "n_am_tot": n_am_tot,
            }
        return {
            "n": n_em_year,
            "ok": False,
            "tau": year_cap,
            "C": cost,
            "E": gR * n_em_tot,
            "n_em_tot": n_em_tot,
            "n_am_tot": n_am_tot,
        }
    }

def best_by_score(plans, c=None):
    c = c or {}
    w = c.get("score_weights", {})
    eps = float(c.get("score_epsilon", 1e-12))
    C = [p["C"] for p in plans]
    T = [p["tau"] for p in plans]
    E = [p["E"] for p in plans]
    c0, c1, t0, t1, e0, e1 = min(C), max(C), min(T), max(T), min(E), max(E)
    def s_linear(v, lo, hi):
        return 1.0 if hi == lo else (hi - v) / (hi - lo)
    def weighted_geometric_mean(values, weights, epsilon):
        total_w = sum(weights)
        if total_w <= 0:
            return 0.0
        acc = 0.0
        for v, wgt in zip(values, weights):
            if wgt <= 0:
                continue
            vv = max(epsilon, v)
            acc += wgt * math.log(vv)
        return math.exp(acc / total_w)
    scored = []
    for p in plans:
        sC = s_linear(p["C"], c0, c1)
        sT = s_linear(p["tau"], t0, t1)
        sE = s_linear(p["E"], e0, e1)
        S = weighted_geometric_mean((sC, sT, sE), (w["cost"], w["time"], w["env"]),
eps)
        scored.append((p, S))
    return max(scored, key=lambda x: x[1])

if __name__ == "__main__":
    fmt = lambda x: f"{x:,.0f}"
    ap = argparse.ArgumentParser(description="Construction-stage model simulation")
    ap.add_argument("--constants", default="construction_constants.json")
    ap.add_argument("--L", type=float, default=None)
    args = ap.parse_args()
    root = Path(__file__).resolve().parent

```

```

with (root / args.constants).resolve().open("r", encoding="utf-8") as f:
    c = json.load(f)
    L = float(args.L) if args.L is not None else float(c["L_max_ton_per_launch"])
    tau_dead = int(c["tau_dead_year"])
    n_cap = int(c["num_rocket_sites"]) * int(c["U_R_launch_per_year_per_site"])
    a_E = float(c.get("a_E", 1.0))
    p_AM = float(c.get("p_AM", 0.0))
    p_EM = float(c.get("p_EM", 0.0))
    plans = [simulate(c, n, L, tau_dead) for n in range(n_cap + 1)]
    feas = [p for p in plans if p["ok"]]
    if feas:
        p, S = best_by_score(feas, c)
        print("Feasible within tau_dead: YES")
        print(f"- n_EM_per_year = {p['n']} launch/year")
        print(f"- tau = {p['tau']} year")
        print(f"- C_total = {fmt(p['C'])} USD")
        print(f"- E_CO2 = {fmt(p['E'])} tCO2")
        print(f"- total n_EM launches = {p['n_em_tot']} launch")
        print(f"- total n_AM launches = {p['n_am_tot']} launch")
        print(f"- Score S = {S:.6f} (0-10)")
        exit()
    print("Feasible within tau_dead: NO")

'''(Ideal situation output)
Feasible within tau_dead: YES
- n_EM_per_year = 865 launch/year
- tau = 15 year
- C_total = 14,553,100,000,000 USD
- E_CO2 = 38,901,000 tCO2
- total n_EM launches = 12967 launch
- total n_AM launches = 53700 launch
- Score S = 5.396377 (0-10)
'''

```
