Problem Chosen	2026 MCM/ICM Summary Sheet	Team Control Number
B		2622082

A Hybrid Earth–Moon Logistics Model Integrating Space Elevators and Reusable Launch Vehicles

Summary

This study develops a mathematical framework to optimize an Earth-Moon transportation architecture combining the Space Elevator (SE) and traditional rockets.

For Problem 1, we established a **Time-Cost Baseline Model** for the hybrid logistics system. Incorporating a **Life Cycle Cost (LCC)** model, results indicate that at 100 reuse cycles, **the total launch cost is reduced to 6%** of expendable vehicles. Consequently, we examined cost-time variations under a concurrent strategy, finding that the model achieves **Pareto Optimality when the Space Elevator Ratio α is approximately 30%.**

For Problem 2, we constructed a **Stochastic Availability and Risk Model**. Introducing physical perturbations (e.g., tether sway, wind speed), Monte Carlo simulations determined the long-term availability to be $\boldsymbol{A_{SE} \approx 0.95}$. We also integrated rocket availability and a Residual Value Loss (RVL) model. Results show highly overlapping solution spaces with maximum relative variation rates for cost and time of **6.46% and 4.72%**, verifying baseline robustness.

For Problem 3, we developed a **Comprehensive Water Demand and Replenishment Model** integrating domestic, agricultural, and industrial needs. Assuming efficient recycling by 2050, we estimated the annual makeup water (losses plus construction lock-up) at **121,765 MT/yr**. This logistical burden incurs an additional cost of **62.84 billion USD** and a timeline extension of **two months**.

For Problem 4, we constructed a **Composite Environmental Impact Assessment Model**. We adopted a single-stage approximation based on the **Tsiolkovsky Rocket Equation** and introduced **pollutant intensity** γ_G to correlate payload with emissions. Environmental index estimates demonstrate that **pollution increases as the rocket proportion rises**, identifying rocket reduction as critical for environmental stewardship.

Sensitivity analysis reveals that while traditional rocket time capacity is relatively insensitive, SE capacity and unit transportation costs are highly sensitive parameters, highlighting key areas for optimization.

Finally, four strategic directives are proposed in the recommendation letter: Adopt a Concurrent Hybrid Logistics Strategy with a 30% Proportional Allocation; Enforce Global Redundancy for Resilience; Establish an Efficient Water Circulation System; and Commit to "Green" Interplanetary Stewardship.

Keywords: Earth–Moon logistics; Space elevator; Reusable launch vehicles; Hybrid transportation system; Stochastic reliability; Environmental impact modeling

Contents

1 Introduction

1.1 Background

With the continued advancement of space technology, establishing a permanent human presence on the Moon has become a feasible engineering objective for the mid-21st century. The problem considers the construction of a lunar settlement capable of supporting approximately 100,000 residents scheduled to begin in 2050 [1].

The construction phase alone requires transporting on the order of 100 million metric tons of materials from Earth to the Moon, a logistical scale far exceeding that of any prior deep-space mission. Such an unprecedented transportation demand places severe constraints on delivery capacity, cost, and sustainability, rendering the choice of Earth–Moon transportation architecture a critical factor in the success of the project.

1.2 Restatement of the Problem

The objective of this study is to develop a mathematical framework to evaluate Earth–Moon transportation strategies for constructing and sustaining a 100,000-person lunar colony beginning in 2050. The analysis focuses on comparing Space Elevator systems, traditional rocket launches, and hybrid configurations in terms of cost, time, reliability, and environmental impact.

Specifically, this study addresses the following tasks:

- **Logistics modeling:** Quantify construction costs and timelines under space-elevator-only, rocket-only, and hybrid transportation scenarios.
- **Robustness analysis:** Evaluate the sensitivity of costs and schedules to stochastic disruptions such as elevator unavailability and launch failures.
- **Sustainment assessment:** Estimate annual water demand for an operational colony and analyze the additional logistics required to supply it.
- **Environmental evaluation:** Assess and minimize the environmental impact of different transportation strategies.
- **Strategic recommendations:** Synthesize results into a concise policy letter recommending an optimal implementation strategy.

1.3 Literature Review

Existing studies on Earth–Moon transportation generally focus on two major technological pathways: conventional rocket-based systems [2] and emerging non-rocket orbital transportation concepts such as space elevators [3].

While rockets remain the most mature and flexible option, they suffer from high costs and environmental burdens [4]. Space elevators, by contrast, have been proposed as a low-emission and low-marginal-cost alternative for large-scale transport, but face significant uncertainties in feasibility and operational constraints [5].

Most existing studies examine these systems independently. Relatively few works place multiple transportation modes within a unified analytical framework for ultra-large-scale, long-term lunar construction. This gap motivates the integrated modeling approach adopted in this study.

1.4 Our work

To avoid complicated description , intuitively reflect our work process, the flow chart is shown as the following Figure 1.

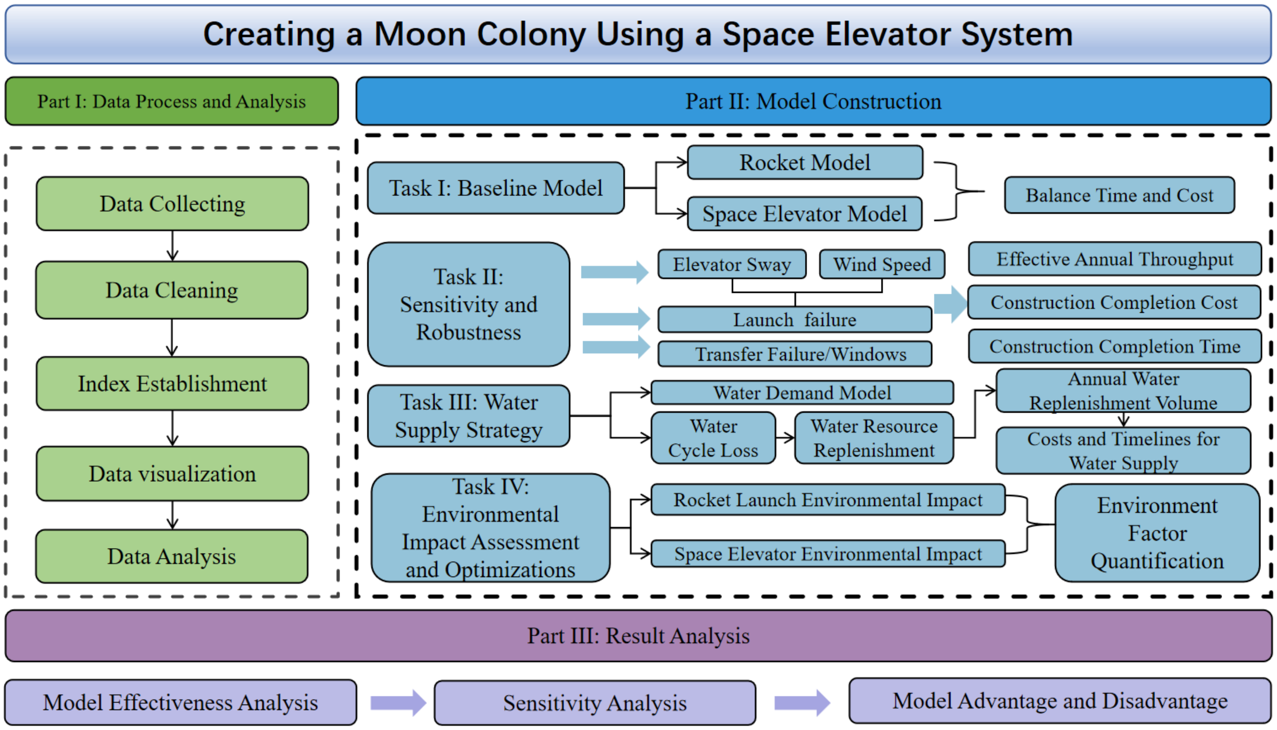

Figure 1: our work

2 Assumptions

2.1 Global Assumptions

1. All construction materials are homogeneous, characterized solely by total mass for transportation modeling.
2. The space elevator and conventional rocket systems operate in parallel, with no mutual interference or shared bottlenecks.
3. Political, legal, and geopolitical factors are not considered in the modeling.
4. Earth has a finite number of active rocket launch sites, each with limited annual launch capacity.
5. Both rocket and space elevator systems are treated as mature, with well-defined input–output characteristics encapsulated in payload capacity, cost, and reliability parameters.
6. For reusable launch vehicles, per-launch cost implicitly includes vehicle manufacturing cost, propellant consumption, and ground operations, with amortized vehicle cost as a fixed fraction.
7. The dry mass of a launch vehicle is modeled as a fixed fraction of the payload mass.

8. Rocket equation is applied only to in-space transfer vehicles.
9. System reliability is modeled as the probability of successful, fault-free missions, with failures assumed to be independent.
10. System reliability is incorporated through an expected-cost formulation.

2.2 Baseline Model Assumptions

1. In the baseline analysis, all transportation capacity and cost parameters are fixed at representative values for the 2050 technology scenario.
2. The allocation parameter α representing the proportion of materials transported via the space elevator is treated as the sole decision variable.
3. All cost parameters remain constant throughout the construction period, with no consideration for inflation, learning effects, or technological advancements.

2.3 Stochastic and Operational Assumptions for Problem 2

1. System performance is divided into availability and mission reliability, where availability is affected by environmental and operational constraints.
2. Environmental disturbances (e.g., wind, cable oscillation) are modeled as stochastic processes affecting system availability.
3. Mission success probabilities vary over time due to operational perturbations and environmental effects.
4. The apex anchor is assumed to function as a buffering and staging node, with no strict temporal synchronization required between the elevator and in-space transfer operations.
5. Routine maintenance is assumed to be scheduled during non-operational windows, with only unscheduled maintenance reducing availability.
6. Failures are incorporated through an expected-cost formulation, using residual value loss as an approximation of economic impact.

2.4 Water Resource Assumptions for Problem 3

By 2050, the space elevator and regolith-to-oxygen technology will mature, eliminating the need for water resource splitting in propellant production.

3 Notations

The core symbols and their definitions used in this study are summarized in Table 1, providing an overview of the key parameters and their related meanings.

Table 1: Notations used in this study

Symbol	**Description**
M	Total mass of construction materials required for the Moon Colony (tons)
h	Height from the vertex anchor to the ground
T_e	Earth's rotation period
T_0	Starting year of the construction phase
R_e	Earth's equatorial radius
N_e	Number of operational space elevator hubs
Q_e	Annual transportation capacity of one space elevator hub (tons/year)
C_e	Unit transportation cost of the space elevator (USD/ton)
ρ_e	Reliability of the space elevator system (probability of failure-free operation)
N_r	Number of active rocket launch sites on Earth
L	Annual number of rocket launches per launch site
P_r	Average payload mass per rocket launch (tons)
P_s	Payload capacity of the in-space transfer vehicle (tons)
C_r	Cost per rocket launch (USD/launch)
ρ_r	Reliability of rocket launches (probability of successful launch)
α	Fraction of total construction materials transported via the space elevator system
T	Total construction time of the Moon Colony (years)
C	Total transportation cost during the construction phase (USD)
$C_{\text{veh}}^{(g)}$	Manufacturing cost of a ground-launched reusable rocket
N_g	Reuse cycles of the ground-launched rocket
$C_{\text{ref}}^{(g)}$	Refurbishment cost per ground rocket launch
$C_{\text{ops}}^{(g)}$	Operational cost per ground rocket launch
$C_{\text{veh}}^{(s)}$	Manufacturing cost of the in-space reusable transfer vehicle
N_s	Reuse cycles of the in-space transfer vehicle
$C_{\text{ref}}^{(s)}$	Refurbishment cost per in-space mission
$C_{\text{ops}}^{(s)}$	Operational cost per in-space mission
c_f	Unit cost of propellant (USD/ton)
$c_{E\to A}$	Unit transportation cost from Earth to elevator apex (USD/-ton)
m_{prop}	Propellant mass required for apex-to-Moon transfer (tons)

4 Problem 1: Baseline model

4.1 Problem Analysis

This problem focuses on the logistical architecture required to transport construction materials from Earth to the Moon within a limited timeframe. We analyze two distinct transportation modes operating in parallel: the Space Elevator, which provides a continuous but fixed-capacity channel, and conventional rockets, which offer flexible but frequency-constrained launch capabilities. The problem is thus modeled as a multi-objective optimization of resource allocation, seeking to balance the competing objectives of minimizing total cost and shortening the construction timeline.

4.2 Model Construction

To enable scalable comparison across different transportation architectures,all cost models are normalized to the expected cost of delivering one metric ton of payload to the lunar surface. System throughput is represented in tons per year, allowing linear scaling with total demand while preserving capacity constraints.

4.2.1 Scenario A: Space Elevator System Only

In this scenario, one metric ton of payload is transported via a space elevator from Earth to the Apex, followed by an in-space tug transferring the payload from the Apex to the lunar surface.

With N_e operational elevator hubs, each providing an annual throughput of Q_e, the total transportation capacity of the space elevator system is:

$$Q_A = N_e \cdot Q_e \tag{1}$$

The total time T_A is determined by:

$$T_A = \frac{M}{Q_A} \tag{2}$$

Let the effective payload mass be m_p. Using the Tsiolkovsky rocket equation, the mass ratio is[6]:

$$R = e^{\frac{\Delta v}{g_0 I_{sp}}} \tag{3}$$

where Δv and I_{sp} denote the velocity increment and specific impulse of the in-space tug, respectively. The specific impulse I_{sp} is a key propulsion performance metric and is strongly influenced by propellant composition and combustion characteristics [7]. Assuming a dry mass m_d, the required propellant mass is:

$$m_{prop} = (R-1)(m_p + m_d) \tag{4}$$

Therefore, the total mass lifted by the space elevator per ton of payload is:

$$m_0 = m_p + m_d + m_{prop} \tag{5}$$

The nominal cost per ton includes elevator lifting cost, tug propellant cost, and amortized vehicle cost. Accounting for the in-space tug R_t, the expected unit payload cost is[8]:

$$\bar{C}_A = \frac{m_0 \cdot c_{E\to A} + \left(m_{prop} \cdot c_{fuel} + \frac{C_{veh}^{(s)}}{N_s}\right)}{R_t} \tag{6}$$

Note that in the Galaxy Port model, cargo is first lifted by elevators to the apogee anchor (100,000 km altitude), then loaded onto lightweight transfer rockets bound for the Moon. According to orbital mechanics, the apogee anchor's velocity is

$$v = w \cdot r = \frac{2\pi}{T_e}(R_e + h) \approx 7.76\text{km/s} \tag{7}$$

while the local escape velocity at that point is

$$v_{esc} = \sqrt{\frac{2GM}{r}} \approx 2.74\text{km/s} \tag{8}$$

Since the apogee anchor's velocity far exceeds the escape velocity at this location, departing from here to the Moon requires almost no additional fuel for acceleration[9].

4.2.2 Scenario B: Traditional Rockets Only

This scenario employs reusable heavy-lift rockets for direct Earth-to-Moon transport. Let N_r denote the number of active launch sites, each supporting L launches per year with an average payload capacity P_r. The total annual throughput is:

$$Q_B = N_r \cdot L \cdot P_r \tag{9}$$

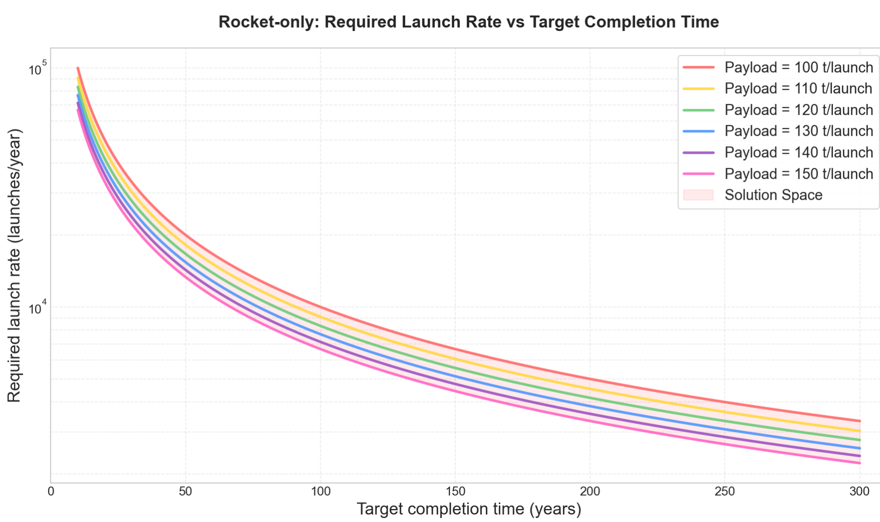

Figure 2: Required annual launch rate vs. target mission duration for 100 million-ton lunar logistics

As Figure 2 illustrates, to meet the demand for transporting hundreds of millions of tons between Earth and the Moon, even utilizing advanced Falcon Heavy launch technology with a payload capacity of 150 tons per launch would require over 3,000 launches annually to reduce the project timeline to 200 years. This poses significant challenges to the cost and production capacity of space transportation systems. Reusability is a crucial approach to addressing issues such as launch costs and production capacity requirements [10].

Based on References [11, 12, 13, 10], we define the full life cycle cost of reusable launch vehicles as follows:

$$
\begin{aligned}
LLC = & C_V + n_1 C_m + n_1(n_2-1)C_w + \\
& n_1(n_2-1)C_h + n_1 n_2 C_c + n_1 n_2 C_q
\end{aligned} \tag{10}
$$

Where LLC represents the total lifecycle cost, n_1 is the number of reusable launch vehicles produced, n_2 is the number of times each vehicle is used, C_V denotes development costs, C_m denotes manufacturing costs, C_w denotes maintenance costs, C_h denotes recovery costs, C_c denotes operational costs, C_q denotes other costs.

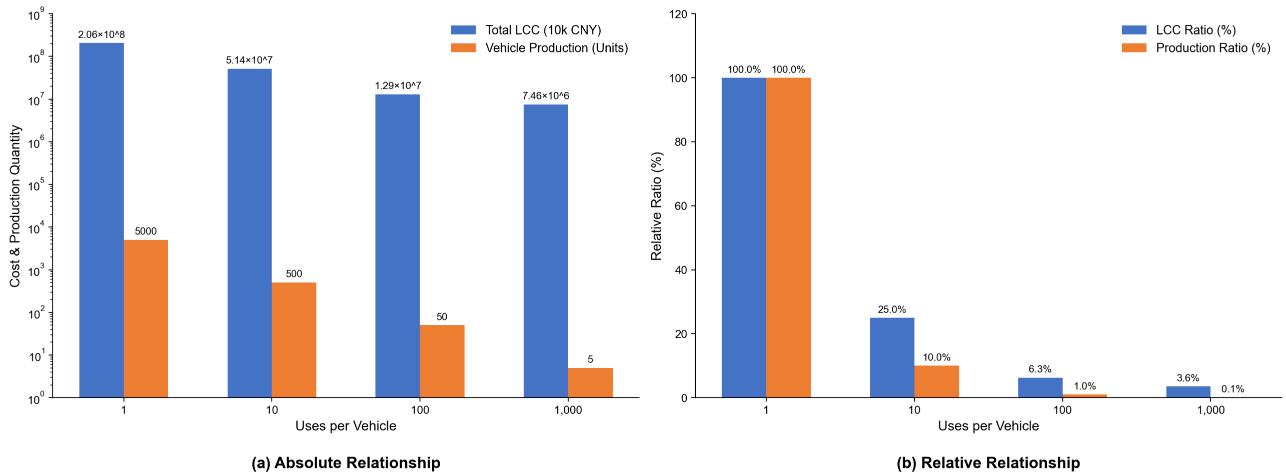

Figure 3: Relationship between total launch cost, production number of launch vehicles and using times of single launch vehicle for 5 000 times of launch

Considering a total demand of 5,000 launches in five years, the calculated lifecycle costs of launch vehicles are shown in Figure 3. It can be seen that as the number of reusable cycles increases, both total launch costs and production capacity requirements continue to decrease. When reusability reaches 100 cycles, total launch costs will drop to 6% of those for single-use launch vehicles, representing a reduction of one to two orders of magnitude.

To facilitate early-stage design trade studies and parametric analyses, the detailed life-cycle cost (LCC) formulation can be reduced to an equivalent per-launch cost representation. Excluding the amortized development cost, the average launch cost can be expressed as

$$
C_{\text{launch}} = \frac{LLC - C_V}{n_1 n_2}. \tag{11}
$$

In practical applications, detailed cost data for manufacturing, refurbishment, recovery, and fixed infrastructure are often unavailable. Therefore, an equivalent hardware cost fraction parameter θ is introduced to represent the portion of the per-launch cost attributable to amortized vehicle hardware:

$$
\theta \equiv \frac{C_{\text{hardware,consumed}}}{C_{\text{launch}}}, \quad 0 < \theta < 1. \tag{12}
$$

For reusable launch vehicles, vehicle hardware is not expended in each mission but amortized over multiple reuse cycles. Accordingly, the hardware cost consumed per launch can be approximated as

$$C_{\text{hardware,consumed}} \approx \frac{C_{\text{veh}}^{(g)}}{N_g}, \tag{13}$$

where $C_{\text{veh}}^{(g)}$ denotes the manufacturing cost of the reusable vehicle hardware and N_g represents the number of reuse cycles.Thus we have:

$$C_{\text{veh}}^{(g)} = \theta \cdot C_{\text{launch}} \cdot N_g \tag{14}$$

The parameter θ thus serves as an equivalent representation of complex hardware-related cost components—including manufacturing cost, fixed infrastructure cost, and part of reuse-related cost—within a simplified system-level cost model. Based on published life-cycle cost analyses of reusable launch vehicles [10, 12], θ is typically assumed to lie within the range $\theta \in [0.2, 0.6]$, with $\theta = 0.4$ adopted as a nominal value in this study.

Assuming a reusable rocket with reuse number N_g, hardware cost allocation factor θ, and launch cost C_{launch}, the expected unit payload cost is:

$$\bar{C}_B = \frac{\theta \cdot C_{\text{launch}}}{P_r \cdot N_g} \tag{15}$$

while the total time T_B is determined by:

$$T_B = \frac{M}{Q_B} \tag{16}$$

4.2.3 Scenario C: Hybrid Strategy

We introduce a decision variable α ($0 \leq \alpha \leq 1$) to represent the proportion of materials transported via the Space Elevator. The remaining fraction $(1 - \alpha)$ is transported via traditional rockets.

Since the two systems operate in parallel, the total completion time T_C is determined by the bottleneck (the slower system):

$$T_C(\alpha) = \max \{\alpha T_A, (1 - \alpha) T_B\} \tag{17}$$

The total cost C_C is the sum of the costs incurred by both methods, utilizing the cost functions derived in previous equations adapted for the respective material portions:

$$C_C(\alpha) = C_A(\alpha M) + C_B((1 - \alpha) M) \tag{18}$$

By optimizing α, we can find the optimal trade-off between construction time and total budget.

4.3 Model Solution

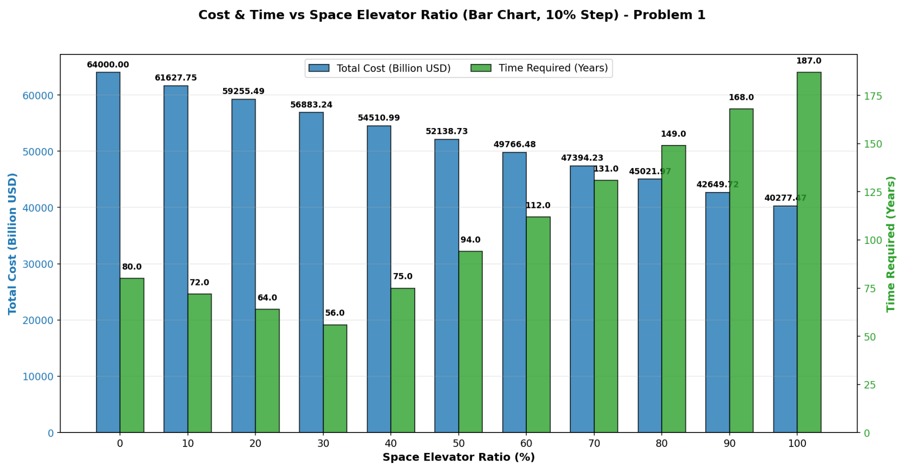

Figure 4: Trade-off Analysis of Total Cost and Time Required under Varying Space Elevator Ratios

The experimental results (see Figure 4) indicate that a space elevator ratio of 30% represents the critical threshold where the system transitions from resource wastefulness to Pareto optimality. Beyond this point, cost and time form a typical trade-off curve. Based on different mission priorities, we offer dual recommendations: For the time-sensitive initial construction phase, we recommend positioning the proportion between 30% and 40%; for long-term operations prioritizing low cost, the focus should shift further toward a pure elevator configuration.

5 Problem2: Stochastic Availability and Risk Model

5.1 Problem Analysis

In Problem 1, a baseline model was established assuming ideal conditions for both the Galaxy Port system (e.g., negligible cable sway) and rocket launches (e.g., zero failure rate). To evaluate system reliability in Problem 2, we introduce stochastic perturbation factors into the model.

5.2 Model Construction

5.2.1 Environmental Constraints and Availability of Space Elevator

Considering the mechanical response of the tether in a realistic space environment, it has been shown that the space elevator payload–tether system exhibits inherent dynamic instability and is highly sensitive to small external disturbances [14, 15]. As a result, environmental perturbations cannot be neglected when assessing system availability. Accordingly, the wind speed v_{wind} is modeled using a Weibull distribution. The tether sway angle $\phi(t)$ is assumed to be linearly driven by wind speed with a noise term $\epsilon(t)$:

$$\phi(t) = k \cdot v_{\text{wind}}(t) + \epsilon(t) \tag{19}$$

The system is considered operational only when the sway angle is within the critical limit ϕ_{crit} and the wind speed is below the safety threshold v_{safe}. We define the availability indicator function $\eta(t)$ as:

$$\eta(t) = \mathbb{I}\left(\phi(t) \le \phi_{\text{crit}} \cap v_{\text{wind}}(t) \le v_{\text{safe}}\right) = \begin{cases} 1, & \text{if operational conditions met} \\ 0, & \text{otherwise} \end{cases} \tag{20}$$

Let A_{SE} be the long-term availability of space elevator. To reasonably estimate A_{SE}, we plotted the following scatter plot based on Monte Carlo simulations:

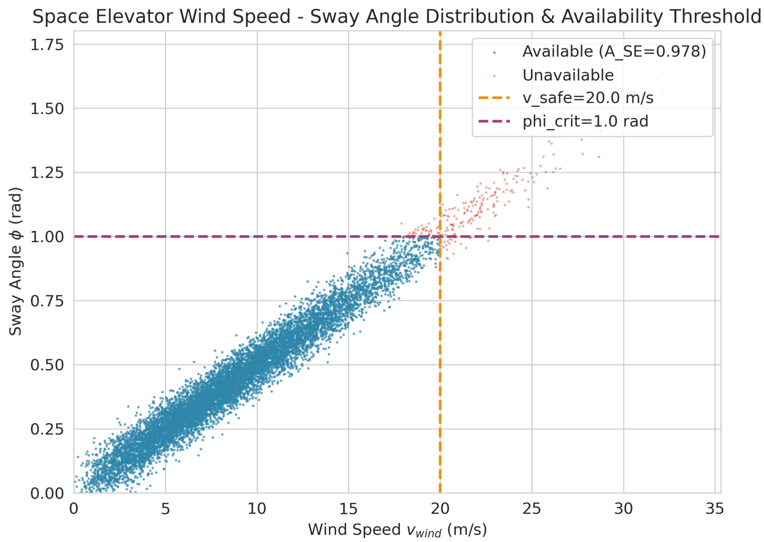

Figure 5: Joint Distribution of Wind Speed and Sway Angle and Availability Domain Division of Space Elevator Based on Monte Carlo Simulation

As shown in Figure 5, most operating conditions fall within the available domain, with a long-term availability factor of $A_{SE} \approx 0.95$. This indicates that the elevator maintains high availability under the constraints of design wind speed and swing angle. High wind speeds and large swing angles collectively constitute the primary sources of unavailability.

Let β_{maint} denote the maintenance downtime ratio, conbined with the long-term availability A_{SE} derived from Monte Carlo simulations, the effective upward throughput of the elevator, $Q_{\text{SE\_eff}}$, is formulated as:

$$Q_{\text{SE\_eff}} = N_{\text{SE}} Q_e (1 - \beta_{\text{maint}}) \cdot \mathbb{E}[\eta(t) \cdot \rho_e(t)] \approx N_{\text{SE}} Q_e A_{\text{SE}} \bar{\rho}_e (1 - \beta_{\text{maint}}) \tag{21}$$

where N_{SE} is the number of tethers, Q_e is the payload capacity, and $\rho_e(t)$ represents the single-trip success probability subject to perturbations.

5.2.2 Risk Assessment and Residual Value Loss for Rockets

For the orbital transfer segment (Vertex Anchor to Moon, denoted as S) and the ground-to-orbit segment (denoted as g), we similarly define availability factors η_S (accounting for micrometeoroids and in-space hazards) and η_g (accounting for launch and translunar injection uncertainties) [16].

We propose a residual value loss model for reusable launch vehicle (RLV). Assuming cargo loss is negligible, the economic impact of a failure focuses on the vehicle asset,which is consistent with re-entry and reuse cost analyses for RLV [17]. If a vehicle with a design life of N missions fails on its n-th mission, the associated cost C_{loss} is calculated based on linear depreciation:

For the orbital transfer vehicle:

$$C_S = C_{\text{veh}}^{(S)} \cdot \frac{N_S - n + 1}{N_S} \tag{22}$$

For the ground-launched rocket:

$$C_g = C_{\text{veh}}^{(g)} \cdot \frac{N_g - n + 1}{N_g} \tag{23}$$

Here, C_{veh} represents the initial manufacturing cost of the vehicle.

5.3 Model Solution

To visually quantify the impact of uncertainty, Figure 6 contrasts the ideal baseline solution space with the stochastic reality.

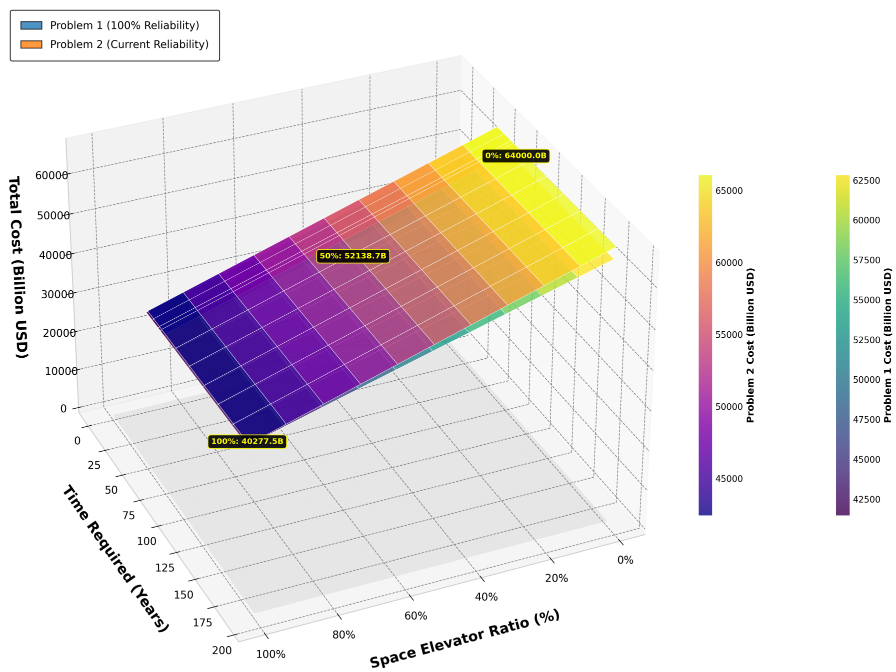

Figure 6: Solution Space Comparison: Ideal Baseline vs. Stochastic Reality

The vertical separation in Figure 6 visualizes the risk premium absorbed by operational failures, inflating the budget by 0.8–3.3 trillion USD. However, the topological consistency between the two surfaces confirms the model's robustness against stochastic perturbations. This demonstrates that while environmental entropy increases the cost, it does not invalidate the fundamental economic superiority of the Space Elevator architecture.

The detailed cost and time defference is shown in table 2 below.

Table 2: Cost and Time Statistics Comparison between Problem 1 and Problem 2

Cost Statistics (Billion USD)		Time Statistics (Years)	
Statistics Index	**Value**	**Statistics Index**	**Value**
Maximum Cost Difference	3368.42	Maximum Time Difference	5.00

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Table 2 continued from previous page

Cost Statistics (Billion USD)		Time Statistics (Years)	
Statistics Index	**Value**	**Statistics Index**	**Value**
Minimum Cost Difference	817.80	Minimum Time Difference	1.00
Standard Deviation	743.63	Standard Deviation	0.95
Maximum Relative Variation Rate	6.46%	Maximum Relative Variation Rate	4.72%

Note: The relative variation rate refers to the maximum percentage change in cost/time between the two problems, where smaller values indicate the minimal impact of reliability variation on the system index.

6 Problem3: Comprehensive Water Demand and Replenishment Model

6.1 Problem Analysis

In this study, we need to investigate the annual water requirements for a fully operational lunar colony housing 100,000 people. At this scale, water resource management transcends basic survival needs and shifts toward enabling habitability and industrialization. We should conduct a thorough assessment to establish a water demand model and evaluate the additional logistical costs and timeline implications.

6.2 Comprehensive Water Demand Model Construction

6.2.1 Model Overview

To construct a water usage model that is as complete as possible, we decompose the demand into three main subsystems: Municipal and Domestic Water, Bioregenerative Agricultural Water, Industrial Water, as shown in Figure 7.

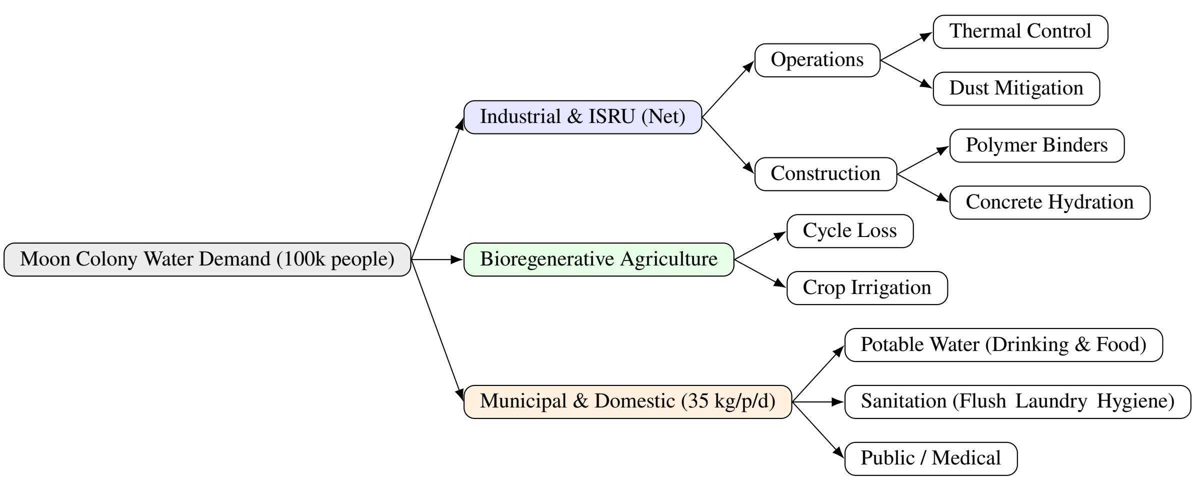

Figure 7: Breakdown of Water Demand Hierarchy in Lunar Colony

6.2.2 Municipal and Domestic Water Demand Model

To ensure the long-term psychological health and social stability of the colony residents, we constructed a comprehensive water use model based on the "Comfort Level Baseline" of developed countries on Earth, encompassing dimensions including drinking, hygiene, laundry, sanitary flushing and public area cleaning.

We define the per capita daily basic water consumption, w_{per_capita}, as a linear superposition of five independent subsystems:

$$w_{per\_capita} = w_{drink} + w_{hygiene} + w_{laundry} + w_{flush} + w_{public} \tag{24}$$

Based on this, the total daily domestic water circulation flux, $Q_{domestic}$, for a population of 100,000 is calculated as follows:

$$Q_{domestic} = P \cdot w_{per\_capita} = P \cdot \sum_{i \in S} w_i \tag{25}$$

Where P is the total colony population, and S is the set of water use categories.

6.2.3 Bioregenerative Agricultural Water Flux Model

Based on experimental data from "Lunar Palace 365" and BIOS-3, we established a basic flux model for the agricultural water cycle.

First, we define α_{land} to be the planting req. Per Capita, thus determine the total planting area A_{total} required to sustain a full diet and 100% oxygen regeneration:

$$A_{total} = P \cdot \alpha_{land} \tag{26}$$

Next, based on irrigation standards for high-efficiency hydroponic systems, we define β_{flux} to be the hydroponic irrigating intensity and calculate the total daily irrigation flux Q_{irrig}:

$$Q_{irrig} = A_{total} \cdot \beta_{flux} = P \cdot \alpha_{land} \cdot \beta_{flux} \tag{27}$$

6.2.4 Industrial and In-Situ Resource Utilization Water Model

Consistent with Assumption 3.1, propellants are excluded from the water budget. We define the annual net industrial water demand W_{ind} as the sum of construction lock-up (W_{const}) and operational losses (W_{ops}):

$$W_{ind} = W_{const} + W_{ops} = P \cdot \Delta A \cdot h \cdot \omega_{conc} \cdot \gamma_{tech} + T_{op} \cdot (Q_{clean} \cdot \eta_{ind\_loss} + E_{cool}) \tag{28}$$

Infrastructure Construction (W_{const}): Water is permanently chemically locked in radiation-shielding structures. Here, $P \cdot \Delta A \cdot h$ denotes the annual construction volume, ω_{conc} is the water content per unit volume, and γ_{tech} is the water-based process ratio.

Operational Losses (W_{ops}): This accounts for irreversible losses from dust mitigation and thermal control. T_{op} (365 days) is the operating cycle, Q_{clean} is the cleaning flux with a loss rate η_{ind_loss}, and E_{cool} represents evaporative cooling consumption.

6.3 Water Cycle Efficiency and Annual Makeup Demand Model

Having established the flux models for each subsystem, the core task of this section is to quantify the Annual Makeup Water W_{makeup}, the actual amount of water that must be replenished annually via Earth transport to maintain the colony's water balance.

We define W_{makeup} as the sum of **irreversible losses** from various recycling subsystems and the **net industrial consumption**:

$$W_{makeup} = W_{loss\_dom} + W_{loss\_agri} + W_{ind} \tag{29}$$

Where W_{loss_dom} is the domestic cycle loss, W_{loss_agri} is the agricultural cycle loss, W_{env} is the environmental physical loss, and W_{ind} is the net industrial demand calculated in the previous section.

$$W_{loss\_dom} = Q_{domestic} \cdot T_{year} \cdot (1 - \eta_{dom}) \tag{30}$$

$$W_{loss\_agri} = Q_{irrig} \cdot T_{year} \cdot (1 - \eta_{agri}) \tag{31}$$

where η_{dom} and η_{agri} represent the domestic and agricultural recovery rate, respectively.

6.4 Model Solution

Figure 8 outlined the proportion of each component in the supplementary water supply.

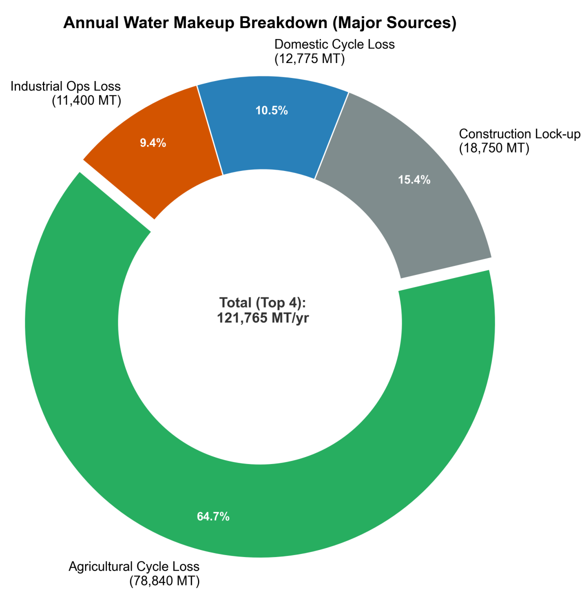

Figure 8: Breakdown of Annual Water Makeup Requirements by Major Loss Categories

After the water demand assessment for the lunar colony, previous delivery model is implemented to calculate the additional costs and timeline required for transporting replenishment water, as shown below.

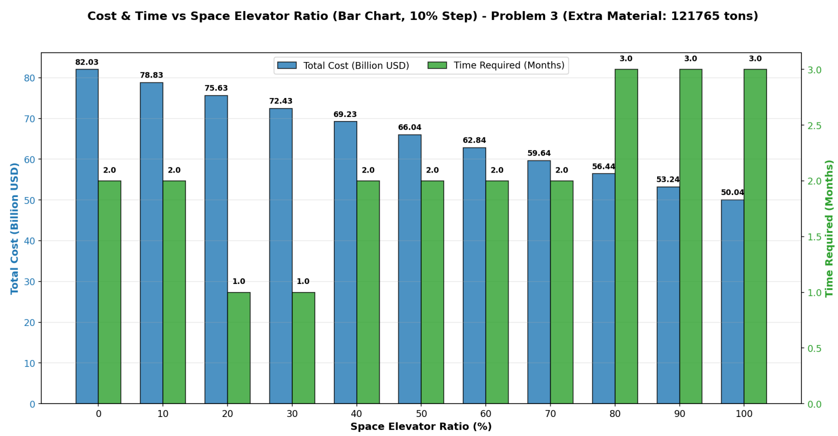

Figure 9: Dual-Objective Sensitivity Analysis of Annual Water Replenishment Logistics

The simulation results in Figure 9 reveal a decisive dominance of economic factors over temporal constraints for the operational phase. As the Space Elevator ratio increases to 100%, the annual logistics cost drops significantly from \$82.03 billion to \$50.04 billion (about 39% reduction). While the purely elevator-based solution extends the delivery window to 3 months compared to the 1-month minimum of a hybrid approach, this temporal penalty is negligible within an annual supply cycle. Therefore, the Cost-Optimal Strategy (**100% Space Elevator**) is recommended for routine water replenishment.

7 Problem 4: Composite Environmental Impact Assessment Model

7.1 Problem Analysis

This section aims to quantify and compare the environmental footprints associated with different transportation modalities. The objective is to provide an evidence-based foundation for the sustainability recommendations presented in the subsequent proposal letter.

Our analysis differentiates between the direct atmospheric injection caused by chemical propulsion and the indirect carbon emissions associated with electric propulsion systems. Specifically, we focus on three subsystems:

- **Ground-based Rockets (TR):** Characterized by high-intensity combustion within the biosphere, directly releasing pollutants into the troposphere and stratosphere.
- **Space Elevator Climbers (SE):** Driven by electricity, where environmental impacts stem primarily from power generation grids.
- **Orbital Tugs (TUG):** Operating in near-vacuum environments.

7.2 Model Construction

To evaluate the aggregate environmental impact, we define a composite environmental index, denoted as E:

$$E = E_{TR} + E_{SE} + E_{TUG} \tag{32}$$

where subscripts TR, SE, and TUG correspond to Ground Rockets, Space Elevators, and Orbital Tugs, respectively.

7.2.1 Atmospheric Interaction and Altitude Coefficients

It is crucial to distinguish the impact mechanisms of ground launches versus orbital operations. Ground rockets release effluents directly into the atmosphere, where species like black carbon (BC) and alumina (Al_2O_3) participate in radiative forcing and ozone depletion chemistry [18, 19]. Conversely, emissions from orbital tugs occur in the exosphere or vacuum, having negligible interaction with the Earth's climate system.

To mathematically represent this disparity, we introduce an altitude-dependent impact coefficient η:

- For ground rockets, $\eta_G = 1$, indicating full atmospheric interaction.
- For orbital tugs, $\eta_O \ll 1$ (approximated as 0 in this study), implying negligible environmental feedback.

Consequently, the term E_{TUG} is omitted from the subsequent calculation of terrestrial environmental impact.

7.2.2 Ground Rocket Propellant Estimation (Single-Stage Approximation)

To quantify the emissions from rocket launches, we first estimate the propellant mass required per unit of payload. Given the uncertainty regarding specific launch vehicle architectures in 2050, we adopt a single-stage approximation based on the Tsiolkovsky rocket equation. This approach provides a closed-form solution that facilitates parameter sensitivity analysis while capturing the primary physics of ascent.

Let m_{pay} denote the payload mass delivered to the target orbit, m_0 the gross liftoff mass (GLOM), and m_{dry} the inert mass (including structure, engines, and avionics). The structural mass fraction ϵ is defined as:

$$\epsilon = \frac{m_{\text{dry}}}{m_0}, \qquad 0 < \epsilon < 1. \tag{33}$$

Considering reusable launch vehicle (RLV) technologies, ϵ typically ranges from 0.08 to 0.15. The propellant mass m_f satisfies:

$$m_f = m_0 - m_{\text{dry}} - m_{\text{pay}} = (1-\epsilon)m_0 - m_{\text{pay}}. \tag{34}$$

Assuming the rocket provides an equivalent velocity increment Δv_G (accounting for gravity and drag losses) with an effective specific impulse $I_{sp,G}$, the mass ratio R_G is given by:

$$R_G = \exp\left(\frac{\Delta v_G}{g_0 I_{sp,G}}\right), \tag{35}$$

Substituting the mass ratio relationship $m_0/(m_{\text{dry}} + m_{\text{pay}}) = R_G$ into the structural fraction definition, we derive the gross liftoff mass:

$$m_0 = \frac{R_G}{1 - R_G\epsilon} m_{\text{pay}}, \tag{36}$$

subject to the feasibility constraint $R_G\epsilon < 1$.

We define the **Propellant Intensity** γ_G (propellant mass required per unit payload) to normalize the analysis:

$$\gamma_G \triangleq \frac{m_f}{m_{\text{pay}}} = \frac{R_G(1-\epsilon)}{1-R_G\epsilon} - 1. \tag{37}$$

This metric allows emission scaling linearly with transport demand, independent of specific vehicle sizing.

7.2.3 Chemical Emission Model for Rockets

The environmental impact of rockets is modeled as a function of propellant composition and combustion efficiency. Let $e_j^{(k)}$ represent the emission index (mass of pollutant j produced per unit mass of propellant k), and let P_k be the mass fraction of propellant type k in the total fuel mix.

We categorize environmental damages into two dimensions: Global Warming Potential (GWP) and Ozone Depletion Potential (ODP). We assign normalized weights ω_{clim} and ω_{O_3} to these categories, respectively. The composite pollution weight for pollutant j is defined as:

$$W_j = \alpha \cdot \omega_{j,\text{clim}} + \beta \cdot \omega_{j,O_3} \tag{38}$$

where α and β are balancing factors (assumed equal, i.e., 0.5, for a simplified comprehensive index).

The total environmental impact of ground rockets, E_{TR}, is calculated by aggregating the weighted emissions:

$$E_{TR} = \sum_k M_{f,k} \left(\sum_j e_j^{(k)} \cdot W_j \right) \cdot \eta_G \tag{39}$$

where $M_{f,k}$ is the total mass of propellant k consumed, derived from the total transport demand M_{total} via $M_{f,k} = M_{\text{total}} \cdot P_k \cdot \gamma_G$.

7.2.4 Indirect Emission Model for Space Elevator

Unlike chemical rockets, the Space Elevator (SE) produces no direct emissions during operation. Its environmental footprint is indirect, stemming from the electricity generation required for the climbers.

The environmental impact E_{SE} is modeled as:

$$E_{SE} = W_{\text{load}} \cdot \Psi_{ele} \cdot \mu_{\text{grid}} \tag{40}$$

where:

- W_{load} is the total mass transported by the elevator.
- Ψ_{ele} is the specific energy consumption (kWh/kg) to lift payload to GEO/Apex.
- μ_{grid} is the carbon intensity of the power grid ($kgCO_2e/kWh$), which varies based on the energy mix scenarios (e.g., fossil-heavy vs. renewables).

Table 3: Classification of Grid Carbon Emission Intensity Scenarios (μ)

Scenario	μ Range (kg CO_2e/kWh)	Description & Basis
S1: Net Zero	$[0.02, 0.10]$	**Strong Mitigation**:a high proportion of renewables and nuclear power (20–100 g/kWh).
S2: Moderate	$[0.10, 0.30]$	**Moderate Transition**: significant clean electricity capacity.
S3: Conservative	$[0.30, 0.60]$	**Weak Policy**: fossil fuels hold a major share.

7.3 Model Solution

To explicitly quantify the ecological drivers within the hybrid logistics system, Figure 10 simulates the variation of the composite environmental impact index across three grid intensity scenarios (S1–S3) as the architecture shifts from an elevator-dominated to a rocket-dominated configuration.

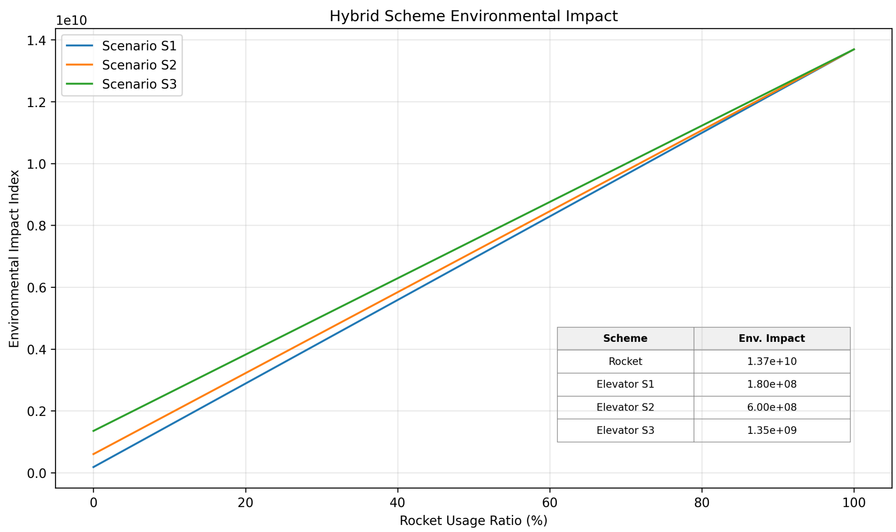

Figure 10: Sensitivity Analysis of Environmental Impact Index: Rocket Usage Ratio vs. Grid Carbon Intensity Scenarios

The results indicate that propulsion modality dominates environmental outcomes, exceeding the influence of power generation sources. As rocket usage increases from 0% to 100%, the environmental impact index rises linearly by two orders of magnitude ($10^8 \sim 1.4 \times 10^{10}$). At this magnitude, the variance between clean (S1) and fossil-heavy (S3) grids is negligible. Consequently, a Space Elevator powered by a conservative grid maintains a lower ecological footprint than chemical rocketry, establishing the reduction of rocket launches as the primary factor in minimizing environmental impact.

8 Sensitivity Analysis

As described in Section 4, the transportation strategy is evaluated using the following formulations for total transportation time T and total transportation cost C:

$$T = \max\left\{\frac{\alpha \cdot M}{Q_{SE}}, \frac{(1-\alpha)\cdot M}{Q_R}\right\} \tag{41}$$

$$C = (\alpha \cdot M \cdot c_{SE}) + ((1-\alpha)\cdot M \cdot c_R) \tag{42}$$

These expressions indicate that system performance is strongly influenced by several time- and cost-related parameters.

To evaluate the robustness of the proposed hybrid transportation system, a sensitivity analysis is conducted by independently varying key parameters (T_R, T_S, C_R, and C_S) within $\pm20\%$ of their baseline values, while keeping all other parameters fixed. The resulting impacts on the normalized comprehensive performance score are illustrated in Fig 11.

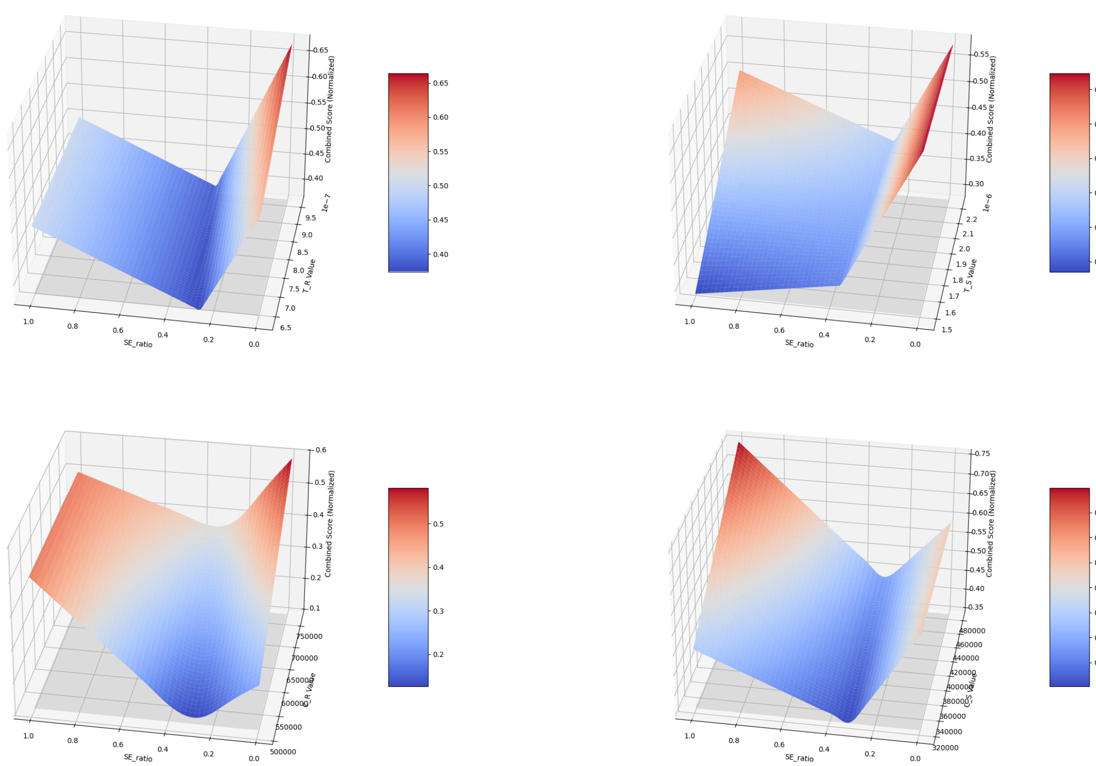

Figure 11: Sensitivity analysis results of key parameters under a time limit of 250 years. The four surfaces correspond to variations in the traditional rocket transportation time T_R, the space elevator transportation time T_S, and the transportation costs C_R and C_S, respectively. The horizontal axis represents the parameter variation ratio, while the vertical axis denotes the proportion of payload assigned to the space elevator system.

From Fig 11, it can be observed that the performance surface associated with T_R exhibits relatively mild gradients, indicating low sensitivity to variations in traditional rocket transportation time. In contrast, pronounced gradients are observed in the surfaces corresponding to T_S, C_R, and C_S, demonstrating that the system performance is highly sensitive to changes in space elevator transportation time and transportation costs.

These results suggest that future engineering optimization efforts should primarily focus on reducing the space elevator transportation time T_S as well as the transportation costs C_R and C_S, as improvements in these parameters yield the most significant gains in overall system-level performance.

9 Model Evaluation and Promotion

9.1 Advantages

After careful examination, our model demonstrates the following distinct advantages:

- ◇ **Unified System Framework:** We successfully established a comprehensive System of Systems (SoS) model that integrates two fundamentally different logistics paradigms into a single framework, effectively solving the complex resource allocation problem.
- ◇ **Strong Robustness:** Unlike static models, our approach incorporates stochastic environmental factors (e.g., wind fields) and utilizes Monte Carlo simulations. This allows our model to remain stable and reliable even under significant uncertainty.
- ◇ **Excellent Visualization:** Our work features rich and intuitive visualizations, such as the 3D trade-off surfaces and the availability scatter plots. These graphics effectively reveal complex non-linear relationships that are difficult to discern from raw data alone.
- ◇ **Scientific Sustainability:** We incorporated a rigorous Life Cycle Assessment (LCA) perspective, distinguishing between direct and indirect emissions. This makes our environmental evaluation far more accurate than simple mass-based calculations.

9.2 Limitations and future work

- ◇ **From Static to Dynamic Economics:** Our current model assumes constant costs to ensure solvability. Future iterations will incorporate **Endogenous Growth Theory** (Learning Curves) to capture how infrastructure costs naturally decrease with cumulative experience and technological maturity.
- ◇ **Technological Fidelity:** Due to the uncertainty of 2050 technology, we relied on historical extrapolations. This model can be upgraded with **Finite Element Method (FEM)** simulations to analyze non-linear tether dynamics under thermal and gravitational perturbations, reducing reliance on estimated parameters.
- ◇ **Scalability to Mars Logistics:** While focused on the Moon, our "High-Thrust vs. High-Efficiency" trade-off framework is highly generic. Future work will extend this topology to **Mars Colonization**, conceptually replacing the Lunar Apex Anchor with a Mars Cycler interface to optimize interplanetary supply chains.

10 Recommendations

We wrote a one-page letter to the fictional Lunar Colonization Authority.

Distinguished Administrators,

The establishment of a permanent lunar settlement for 100,000 residents represents not merely an engineering milestone, but the next logical step in human evolution. Following a comprehensive feasibility study encompassing logistics optimization, stochastic risk assessment, and environmental impact analysis, our team has concluded that success lies not in choosing between Earth-based rocketry and the Space Elevator, but in the intelligent integration of both.

To ensure the viability of the 2050 initiative, we submit the following strategic directives:

1. Adopt a Concurrent Hybrid Logistics Strategy with Proportional Allocation

We advise against relying on a single transportation modality. Instead, we recommend a **concurrent hybrid logistics architecture**, in which Earth-based rockets and the Space Elevator operate simultaneously from the outset. Within this concurrent framework, the two systems assume distinct functional roles:

- **Rocket-dominated allocation:** Rockets prioritize time-critical, high-value, and infrastructure-enabling payloads, leveraging their operational flexibility.
- **Elevator-dominated allocation:** The Space Elevator carries bulk, low-priority, and environmentally sensitive cargo, benefiting from its low marginal cost and minimal atmospheric impact.

Our modeling indicates that a **30% Space Elevator utilization ratio** represents the **Pareto Optimal** point—the specific balance where construction costs are minimized without unacceptable delays to the project timeline.

2. Enforce Global Redundancy for Resilience

While the Space Elevator is efficient, our simulations reveal a weather-induced unavailability rate of approximately 5%. To mitigate supply chain paralysis during these outages, the LCA must maintain a **Global Disaster Preparedness Network**. We recommend maintaining active, rapid-response launch capabilities at **Florida (USA), Kourou (French Guiana), and Taiyuan (China)**. This geographic diversity ensures that when one corridor closes, another opens.

3. Establish an Efficient Water Circulation System

Hydrological analysis and projections indicate that, based on an efficient water circulation system, only **121,765 metric tons** of water resources need to be replenished annually. This volume can be transported via the space elevator, incurring an additional cost of **62.84 billion USD** and extending the construction period by **2 months**. We strongly recommend establishing a comprehensive water circulation system at the outset of construction to transition the outpost from an "import-dependent" facility to a self-sufficient entity.

4. Commit to "Green" Interplanetary Stewardship

To mitigate cumulative stratospheric damage from chemical launches, we propose an **environmental compensation mechanism**, complemented by the inherently low-emission profile of the electric Space Elevator. For rocket missions that remain operationally indispensable, priority should be given to cleaner propulsion technologies to reduce per-launch black carbon and NO_x emissions without sacrificing mission flexibility.

We are not merely building a base; we are constructing a bridge between worlds. This roadmap ensures that bridge is built on economic efficiency, operational resilience, and environmental responsibility.

Respectfully,

Team #2622082

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Appendix A: Historical Rocket Launch Statistics

This appendix summarizes historical global rocket launch statistics used to inform reasonable parameter ranges in the main model. The data are aggregated over multi-year periods to highlight overall trends in launch activity and success rates. Due to the long time horizon of the study and the absence of authoritative forecasts for the year 2050, these historical data are not used for deterministic prediction, but rather to provide qualitative and quantitative support for baseline parameter selection and sensitivity analysis.

Table 4: Global Rocket Launch Statistics (2000–2025)

Year	Total Launches	Success Rate (%)	Year	Total Launches	Success Rate (%)
2000	85	95.29	2013	81	96.30
2001	59	94.92	2014	93	95.70
2002	65	92.31	2015	86	94.19
2003	63	96.83	2016	85	96.47
2004	55	92.73	2017	91	92.31
2005	55	94.55	2018	114	96.49
2006	67	92.54	2019	102	94.12
2007	68	92.65	2020	114	91.23
2008	69	94.20	2021	145	92.41
2009	78	93.59	2022	186	95.70
2010	74	94.59	2023	222	95.50
2011	84	91.67	2024	259	96.91
2012	78	93.59	2025	324	97.22

Report on Use of AI

1. **DeepL**
   We use DeepL to translate the paper into English.

2. **Deepseek**
   Query: Please proofread and polish the Abstract and Introduction sections of this paper. Focus on improving grammar, sentence structure, and academic vocabulary.
   Output: The AI identified grammatical errors and suggested more precise terminology. It provided a refined version of the text, which we reviewed and adopted to ensure the paper meets the linguistic standards of an academic submission.

3. **Github CoPilot (2026 version)**
   Auto-completions and hints for code used in preparing our models.

4. **Gemini (2026 version)**
   Query: Suggest academic search keywords for modeling a lunar colony logistics system based on space elevators and rockets.
   Output: The AI provided a structured list of keywords including "Geosynchronous Tether Dynamics," "High-Specific-Strength Materials," "Propellantless Orbital Transfer," and "Bioregenerative Life Support Systems." These keywords guided our literature review to find essential parameters for model construction.

5. **GPT-5 mini**
   Code generation for complex latex formula.

6. **Nano Banana (Feb 2, 2026 version)**
   Query: Generate a futuristic A4 letterhead that balances a high-tech interstellar theme with maximized white space for writing. Header: Top Left: A highly detailed but compact emblem symbolizing interstellar ambition... Body/Background: A full A4 size page... The main writing area is predominantly bright, pure white... Footer: At the bottom edge, another identical thin, glowing electric blue horizontal line...
   Output: The AI generated a high-resolution image of a futuristic letterhead featuring a minimalist lunar base logo, a subtle hexagonal grid watermark, and glowing blue accents. We saved this image as `letter5.png` and used the `TikZ` package to apply it as the background for the recommendation letter.

7. **Doubao**
   Query: Generate TikZ code for this structure (lower height): Moon Colony Water Demand (100k people)

```
Moon Colony Water Demand (100k people)
 Industrial & ISRU (Net Consumption)
   Operations
     Thermal Control
     Dust Mitigation
   Construction
      Polymer Binders
      Concrete Hydration

 Bioregenerative Agriculture
```

```
   Cycle Loss
   Crop Irrigation

 Municipal & Domestic (35 kg/p/d)
    Public/Medical
    Flush
    Laundry
    Personal Hygiene
    Drinking & Food
```

Output: Introduction section:

```
\usepackage{forest}
\usepackage{tikz}
\usetikzlibrary{arrows.meta}
```

TikZ diagrams in the main text:

```
\begin{figure}[H]
\centering
\begin{forest}
for tree={
    grow'=east,
    draw,
    rounded corners,
    align=left,
    font=\scriptsize,
    edge={-Latex},
    parent anchor=east,
    child anchor=west,
    anchor=west,
    l sep+=6pt,
    s sep+=0.6pt,
    inner ysep=0.8pt,
    inner xsep=6pt,
}
[
Moon Colony Water Demand (100k people),
    fill=gray!15,
    [
        Industrial \& ISRU (Net),
        fill=blue!10,
        [
            Operations,
            [Thermal Control]
            [Dust Mitigation]
        ]
        [
            Construction,
            [Polymer Binders]
            [Concrete Hydration]
        ]
    ]
    [
        Bioregenerative Agriculture,
        fill=green!10,
        [
            Cycle Loss
        ]
        [
            Crop Irrigation
        ]
    ]
    [
    Municipal \& Domestic (35 kg/p/d),
    fill=orange!12,
    [
        Potable Water (Drinking \& Food)
    ]
    [
        Sanitation (Flush\, Laundry\, Hygiene)
    ]
    [
```

```
          Public / Medical
     ]
     ]
]
\end{forest}
\caption{Breakdown of Water Demand Hierarchy in Lunar Colony}
\label{fig:mindmap}
\end{figure}
```