

# Establishing a lunar colony using hybrid transportation methods

## Summary

This paper addresses the problem of establishing lunar colonies using a space elevator system, which essentially constitutes a cost minimisation linear programming problem under cargo capacity constraints. A mathematical model for mixed-material transport has been developed, with optimal time as the objective. The specific research content is as follows:

First, we coupled a continuous flow system (space elevator) with a discrete batch transport system (rocket launch). Subject to the constraint of total cargo volume, we developed a hybrid transport model capable of addressing multiple scenarios, resolving at least the following four problems:

**For Question 1:** Under ideal conditions, **the hybrid mode (space elevator and rocket) has obvious advantages** — it reduces transport time to about 70 years and keeps costs moderate, outperforming either a pure elevator or a pure rocket solution. For the time and cost of other transportation methods, you can refer to Table 1.

**For Question 2:** Took the initial scenario a step further by factoring in real-world system availability, represented by a disturbance coefficient. Once this practical constraint was added, the mission timelines extended to 196 years, 113.38 years, and 71.83 years, with corresponding costs of  $1.015 \times 10^{11}$ ,  $5 \times 10^{11}$ , and  $3.59 \times 10^{11}$  you can refer to Figure 2 for details. The hybrid method still came out on top for speed, with its cost falling between the other two options. An important shift here is that the pure space elevator's advantage shrank noticeably once disturbances were part of the equation. Under these more realistic, non-ideal conditions, the hybrid approach clearly stands out as the best balance of time and cost.

**For Question 3:** After incorporating life support and environmental objectives, **the hybrid model was once again proven to be the fastest**, requiring only 0.56 years. The transportation costs and times for other methods and conditions can be found in Tables 3 and 4. At the same time, a key finding is that in this hybrid framework, assigning more cargo to the elevator can **significantly reduce the total mission cost**.

**For question 4:** In most cases, the hybrid approach really does strike the best balance between cost and time. But when we look at environmental impact, the differences between the three options are pretty dramatic. In terms of total CO<sub>2</sub>e emissions after building the lunar colony and running a year of water resupply: Using only the Galactic Port (“space elevator”) comes out to around 1,007.85 million tonnes. Traditional rockets alone emit a massive 322,511.20 million tonnes. The fastest hybrid option lands at 202,027.98 million tonnes. So even though the hybrid method is already the fastest, it also beats rockets hands-down on emissions, while still being way quicker than relying solely on the elevator. **That tells us the space elevator system isn't just fast — it's also a much cleaner alternative.** For the detailed breakdown, you'd want to check Table 5 (ideal case) and Table 6 (with disturbance factors).

The model system constructed herein features **efficient solution methods and clear hierarchical structure**. The derived strategies yield effective outcomes in evaluating space transport scheme performance and optimising parameters, providing **not only efficient solutions for transport challenges but also demonstrating practical feasibility for real-world applications**.

**Keywords:** Hybrid transport model; Space elevator; Resource allocation; Linear programming

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# 1 Introduction

## 1.1 Assumptions and Symbols

The space elevator system is a concept for the construction of a lunar colony with a projected capacity of 100,000 people after the year 2050. This undertaking would necessitate the procurement and transportation of approximately one billion tonnes of construction materials. Two primary methods have been proposed for the conveyance of these materials. Firstly, the utilisation of a future space elevator system, capable of transporting 179,000 tonnes annually without compromising the integrity of the atmosphere. Secondly, the employment of contemporary heavy-lift rockets, with a capacity ranging from 100 to 150 tonnes, launched from ten distinct locations.

Our task is to build a mathematical model to calculate the cost and time required to transport these materials to the Moon starting from 2050. We need to consider three scenarios: using only a space elevator; using only traditional rockets; and using both together. The model should take into account both perfect conditions and conditions with disturbances. After the base is built, we also need to calculate the additional cost and time for operating water transport. Additionally, we need to assess the impact of the transportation methods on the Earth's environment and figure out ways for the model to minimize environmental damage. Finally, we need to write a decision recommendation letter to the MCM.

## 1.2 Ourwork

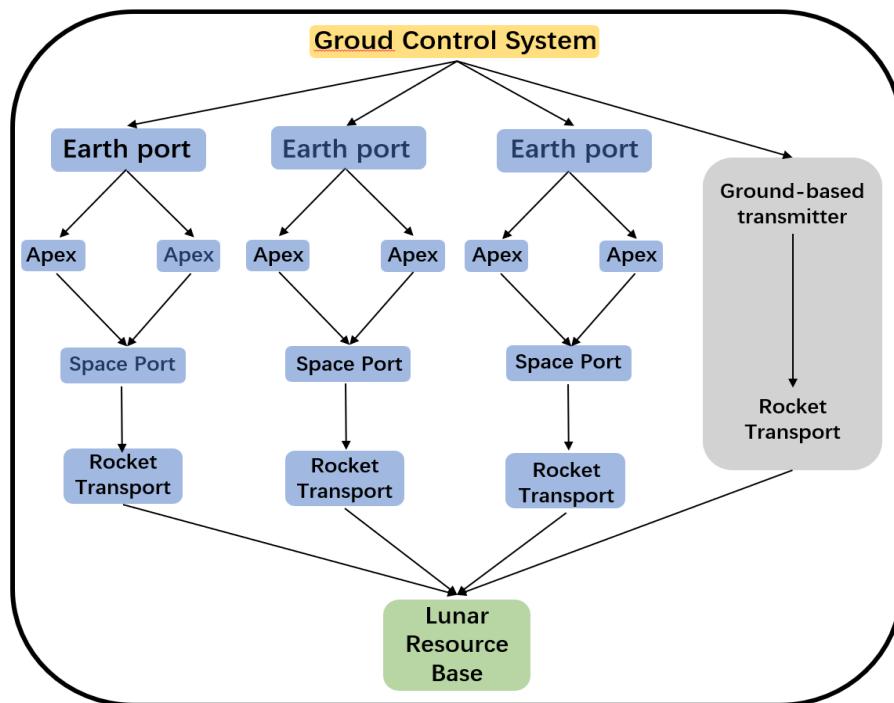


Figure 1: Flowchart

In accordance with the specified scenario, the procedural sequence has been delineated in Figure 1. This figure meticulously delineates the precise procedures that have been followed by both modes of transport in the Earth-Moon material delivery operation. This established

sequence of thought processes is characterised by its rigorous nature, with all subsequent stages strictly adhering to the stipulated flowchart.

## 2 Assumptions and Symbols

### 2.1 Model Hypothesis

It is assumed that the average launch cost from a rocket launch site to the Moon is \$5,000 per kilogramme<sup>[1]</sup>. By comparison, the transport cost under the space elevator project is \$500 per kilogramme<sup>[2]</sup> (delivered to Galaxy Port). According to the Tsiolkovsky rocket equation, the cost of transporting cargo from Galaxy Port to the Moon is calculated to be \$515 per kilogramme.

It is hypothesised that the Earth Current rocket launch sites have the capacity to operate at full capacity<sup>[3][4]</sup>, with rockets being launched twice daily<sup>[5]</sup> and Falcon Heavy rockets being selected for material transport.

In the ideal scenario, both alpha and beta are equal to 1 (a fact that has not been explicitly demonstrated in the formula). However, under more optimistic conditions,  $\alpha$  is set at 0.95, while  $\beta$  is set at 0.98.

### 2.2 Symbols and Definitions and Unit

Symbols	Description
$M_{total}$	Total mass of materials required for the corresponding scenario
$M_i$	Quality allocated to the system in the corresponding context $i$ ( $i \in \{a, b\}$ )
$R_i$	Annual transport rate of system $i$ ( $i \in \{a, b\}$ )
$T_i$	Total duration for scenario $i$ ( $i \in \{a, b, c\}$ )
$D_i$	Total cost for scenario $i$ ( $i \in \{a, b, c\}$ )
$f_i$	Operational frequency of system $i$ ( $i \in \{a, b\}$ )
$N_{rk}$	Total number of rocket launches required
$P_i$	Actual annual capacity of system $i$ under imperfect conditions ( $i \in \{a, b\}$ )
$c_i$	Unit transport cost of system $i$ under imperfect conditions ( $i \in \{a, b\}$ )
$T_x$	Transport duration for scenario $i$ under imperfect conditions ( $x \in \{a, b, c\}$ )
$C_i$	Total transport cost for scenario $i$ under imperfect conditions
$x$	The load capacity is within the range of 100 to 150 tonnes.

## 3 Problem Analysis and Model Development and Solution

Following a comprehensive review of the pertinent documentation, it has been determined that the financial and temporal implications of transporting goods vary according to the selected

mode of conveyance. Consequently, in instances where the quantity of goods is fixed and the mode of transport is predetermined, the total cost should also be fixed. Utilising this information, we can establish the parameters for examining three potential scenarios for each of the two transport methods.

- **Solution for scenario i**

It is estimated that each Galaxy Port system possesses the capacity to facilitate the transportation of 179,000 tonnes of cargo from Earth to the Moon on an annual basis. This two-stage transportation process is deemed to be complete only upon the successful delivery of the shipment from the Galaxy Port to the Moon. Consequently, the annual frequency of rocket launches within the confines of the Galaxy Port system can be determined as follows

Under ideal conditions:

$$f_a = \frac{17900}{x}$$

In light of the disturbance factors present in real-world scenarios, the disturbance coefficient alpha is hereby introduced. Consequently, the annual emission frequency is determined as follows

$$f_{a1} = \alpha f_a \frac{17900\alpha}{x}$$

The time required for its transportation is (when the parameter known as  $\alpha$  is set to one, i.e. under conditions deemed ideal)

$$T_a = \frac{M_{total}}{3f_a x} = \frac{M_{total}}{537000\alpha} \quad (1)$$

The financial requirements for this mode of transport have been addressed

$$D_a = M_{total} \times (M + m) \quad (2)$$

- **Solution for scenario ii**

It is estimated that a rocket launch site is capable of conducting two launches per day. Therefore, the annual launch frequency for a rocket launch site is as follows

$$f_b = 720$$

In order to account for disturbances present in real-world scenarios, the disturbance coefficient  $\beta$  is hereby introduced. The annual emission frequency is thus given by

$$f_{b1} = \beta f_b$$

The time required for this mode of transport is as follows

$$T_b = \frac{M_{total}}{10x\beta f_b} \quad (3)$$

The corresponding costs required shall satisfy the following conditions

$$D_b = M_{total} \times 5000 \quad (4)$$

- **Solution for scenario iii**

Assuming that the Solution for scenario i is equally successful as that for scenario b, the following equation is obtained

$$M_a + M_b = M_{total}$$

In the context of integrated transportation systems involving a combination of two or more modes, there exists

$$T_c = \max\left\{\frac{M_{total}}{3f_{a1}x} \frac{M_a}{M_{total}}, \frac{M_{total}}{10f_{b1}x} \frac{M_b}{M_{total}}\right\} = \max\left\{\frac{M_a}{3\alpha f_a x}, \frac{M_b}{10\beta f_b x}\right\} \quad (5)$$

The cost of this mode of transport shall satisfy the following criteria

$$D_c = D_a + D_b = M_a \times (M + m) + M_b \times 5000 \quad (6)$$

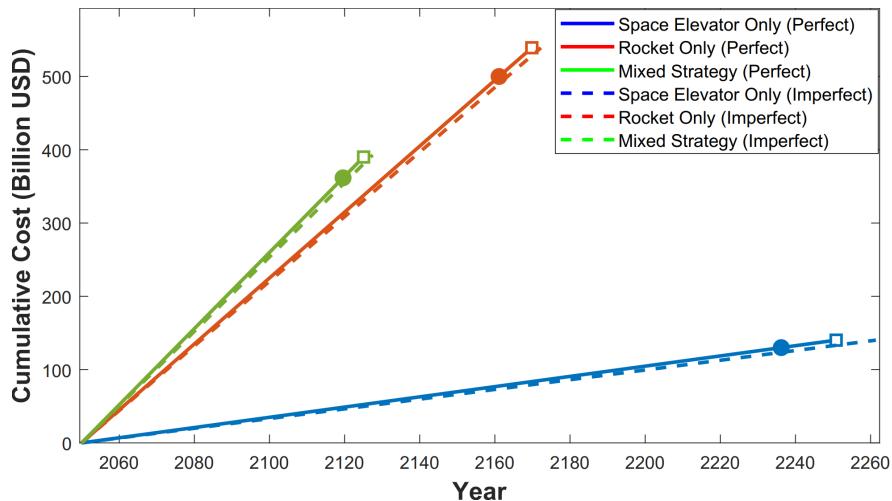


Figure 2: 10 year cost schedule for lunar colonisation

It is hypothesised that the rocket will have a payload capacity of 125 tonnes and will be operational for a period of 10 years following completion. The costs and time requirements will adhere to the relationship depicted in the diagram. When both transport methods are employed concurrently, the cost will fall between the two and the time consumption will be negligible.

## 4 Use for several specific issues

### 4.1 Performance Evaluation of Transport Schemes and Multi-Criteria Decision-Making

#### 4.1.1 Problem Analysis

In this context, it can be deduced that both  $\alpha$  and  $\beta$  are equal to one, and neither is reflected in the following expression.

- **Solution for scenario i**

It is evident that each Galactic Port is capable of handling a sufficient annual cargo volume to transport 179,000 metric tonnes of material. Consequently, the time required to deliver the necessary materials can be calculated. It should be noted that Galactic Port shipments involve two distinct stages with differing costs. Therefore, the cost for Scenario a should be the sum of both stages' costs.

The duration of transportation when utilising solely the space elevator system is as follows

$$T_a = \frac{M_{total}}{R_a}$$

The total cost of building a space elevator is the cost of the elevator itself from Earth to the Moon, and the cost of the rocket from the Moon back to Earth. If we use a soft landing material, the cost is calculated like this

$$D_a = 1015M_{total}$$

- **Solution for scenario ii**

In consideration of the ten rocket launch sites currently in operation on the Earth, the launch frequency of each rocket, and the payload capacity of the latter, the time required for the transportation of materials can be calculated. With the launch frequency and required time as known constants, the number of rocket launches can be determined. This, in turn, enables the calculation of the cost of transporting materials using only traditional rockets.

It is imperative to note that when utilising the Earth Current rocket launch site in isolation, the designated transportation time is as follows

$$T_b = \frac{M_{total}}{R_b}$$

The total number of rocket launches is

$$N_{rk} = 10 \times f_b \times T_b$$

The transportation cost using solely the Earth Current launch site can be calculated as follows

$$D_b = M_{total} \times 5000$$

- **Solution for scenario iii**

The hybrid approach combines two transportation methods, with both schemes operating concurrently to convey specific quantities of goods. As the allocation of goods differs between the two schemes, the duration of the hybrid operation is determined by the scheme that requires the longest duration. The cost of the hybrid scheme is determined by the specific quantities of goods transported by each scheme.

In order to initiate simultaneous transport operations, it is necessary to combine both approaches. The 100 million tons of cargo are divided into  $N_a$  and  $N_b$ . From the time required to transport 100 million tons as determined by To scenarios a, it is possible to derive the time

needed to transport  $N_a$  tons. Similarly, by applying To scenarios b, it is possible to calculate the time required to transport  $N_b$  tons of material. These times are respectively

$$W_a = \frac{R_a}{R_a + R_b} M_{total} \quad W_b = \frac{R_b}{R_a + R_b} M_{total}$$

By combining the linear inequalities, the total transport time can be derived as

$$T_c = \frac{M_{total}}{R_a + R_b}$$

As demonstrated in the accompanying diagram, in order to minimise the total transport time, it is necessary for both scenarios to commence simultaneously and conclude their respective transport tasks concurrently. The total cost of the hybrid model is derived by combining the cost calculation formulas for Scenario A and Scenario B as follows

$$D_c = T_c \cdot (1015R_a + 5000R_b) = M_{total} \times \frac{1015R_a + 5000R_b}{R_a + R_b}$$

#### 4.1.2 Solving models

Substituting the scenario into all the above equations  $M_{total} = 10^8$ ,  $x = 125$ ,  $\alpha = 1$ ,  $\beta = 1$

Table 1: Time Cost Statistics

proposal	Delivery time(years)	Delivery cost(\$)
<b>Solution for scenario i</b>	186.22	$1.015 \times 10^{11}$
<b>Solution for scenario ii</b>	111.11	$5.000 \times 10^{11}$
<b>Solution for scenario iii</b>	69.59	$3.510 \times 10^{11}$

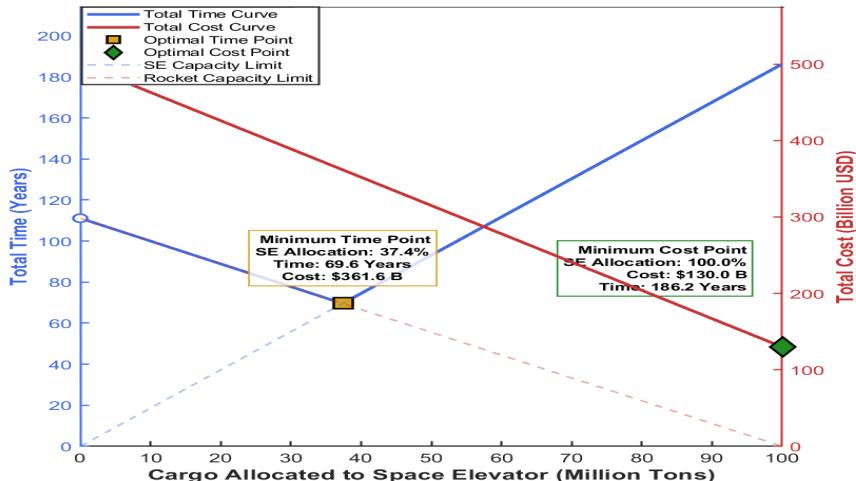


Figure 3: Relationship between space elevator allocation, time, and cost

#### 4.1.3 Analysis of Results

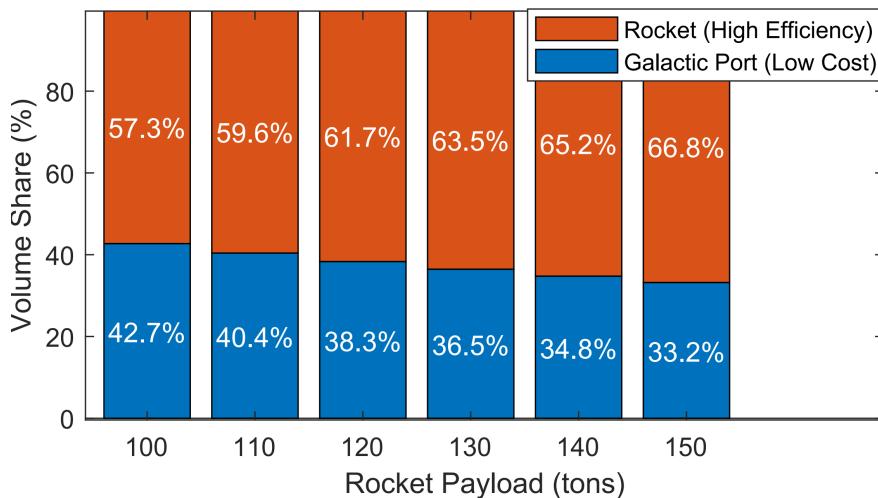


Figure 4: Capacity allocation ratio

We can see that the larger the payload, the heavier the mission the rocket has to undertake. Assuming that the unit transport cost of the space elevator is lower than that of conventional rockets, it is demonstrated that the Galaxy Port system alone yields the lowest total cost, followed by the hybrid approach, with the traditional rocket-only solution being the most expensive.

Should establishing a lunar colony as swiftly as possible after 2050 be the primary objective, it is recommended that the hybrid transport scheme be selected. This offers the optimal timeline, enabling the delivery of all materials within approximately 70 years, while its cost lies between the two alternatives, presenting favourable overall feasibility.

Therefore, under ideal conditions, the hybrid transport model combining the Galaxy Port system with conventional rockets is recommended as the preferred approach for establishing a 100,000-person lunar colony.

## 4.2 Construction of hybrid transportation models based on different scenarios

### 4.2.1 Problem Analysis

The crux of Question 2 pertains to the quantitative evaluation of the impact of system reliability on the efficacy of transport solutions. It is imperative to integrate reliability parameters into the original model to analyse the variation in transport time and costs across three scenarios (Galaxy Port only, Rocket only, and hybrid solution) under varying failure levels. This will establish a foundation for effective project risk management.

The core idea is to introduce a coefficient ( $0 < coeff \leq 1$ ) that represents the "uptime" or "success rate," which effectively reduces capacity and increases unit cost.

**Galactic Harbor ( $\alpha$ ): Represents availability (affected by tether sway, maintenance).**

**Rocket System ( $\beta$ ): Represents success probability (affected by launch failures).**

- Solution for scenario i:

Galactic Harbor (with disturbance  $\alpha$ ) The disturbance reduces the effective rate and increases the unit cost inversely.

Effective Annual Capacity

$$P_a = \alpha \cdot R_a$$

Transport Time

$$T_a = \frac{M_{total}}{P_a}$$

Unit Cost (Disturbed)

$$c_a = \frac{D_a}{\alpha}$$

Total Cost

$$c_a = M_{total} \cdot c_a$$

- **Solution for scenario ii:**

Rocket System (with disturbance  $\beta$ )

Effective Annual Capacity

$$P_b = \beta \cdot R_b$$

Unit Cost (Disturbed)

$$c_b = \frac{D_b}{\beta}$$

- **Solution for scenario iii:**

Hybrid Correction The hybrid model optimizes by equating the transport times of both systems ( $T_c$ ) to ensure simultaneous completion.

Constraint

$$\frac{M_a}{P_a} = \frac{M_b}{P_b} = T_c$$

Total Time

$$T_c = \frac{M_{total}}{P_a + P_b}$$

Load Allocation

$$M_a = \frac{P_a}{P_a + P_b} \cdot M_{total} \quad M_b = \frac{P_b}{P_a + P_b} \cdot M_{total}$$

The total cost of a hybrid system under disturbance conditions can be expressed as

$$C_{total} = \left( \frac{P_a \cdot M_{total}}{P_a + P_b} \right) \cdot \frac{D_a}{\alpha} + \left( \frac{P_b \cdot M_{total}}{P_a + P_b} \right) \cdot \frac{D_b}{\beta}$$

#### 4.2.2 Solving the model

In order to quantify the impact of imperfect conditions, two sets of reliability parameter scenarios are established for analysis purposes. The first scenario is optimistic, with relatively high system reliability ( $\alpha = 0.95$ ), and the second is conservative, with relatively low system reliability ( $\beta = 0.90$ ). The specific parameter values and their rationale are as follows:

**Optimistic Scenario:** As an emerging yet mature technology, Galaxy Port exhibits high availability ( $\alpha = 0.95$ ); rocket launch technology, having developed over decades, is highly reliable ( $\beta = 0.98$ ).

Substituting the scenario into all the above equations:  $M_{total} = 10^8$ ,  $x = 125$ ,  $\alpha = 0.95$ ,  $\beta = 0.98$ .

Table 2: Time cost statistics

proposal	Delivery time(years)	Delivery cost(\$)
<b>Solution for scenario i</b>	196.02	$1.015 \times 10^{11}$
<b>Solution for scenario ii</b>	113.38	$5.000 \times 10^{11}$
<b>Solution for scenario iii</b>	71.83	$3.539 \times 10^{11}$

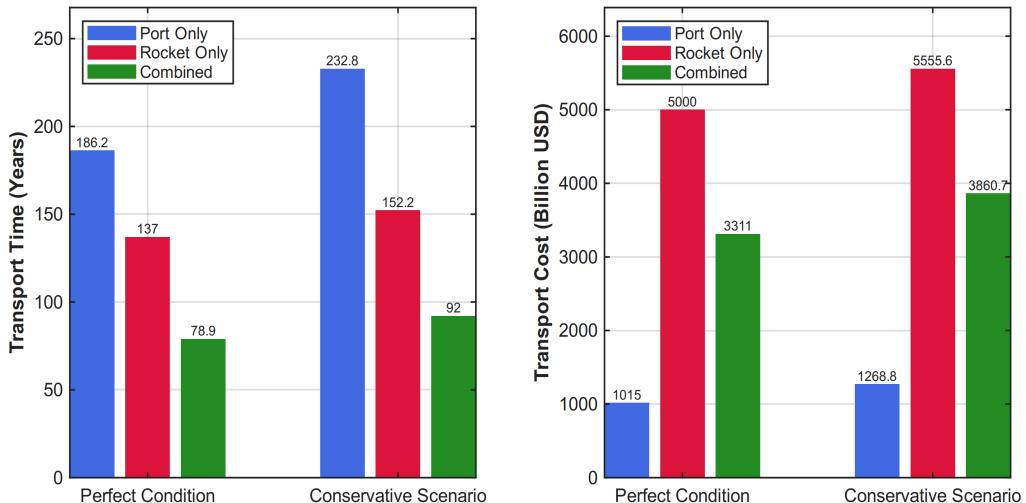


Figure 5: Cost and time comparison

#### 4.2.3 Analysis of Results

In circumstances that deviate from ideal conditions, the conclusions derived from Problem 1 are subject to modification. When utilising the space elevator as the sole means of transportation, there is a considerable fluctuation in the time cost, resulting in instability. Conversely, the hybrid strategy demonstrates minimal variation, ensuring consistent delivery times. Consequently, our solution remains unaltered.

## 4.3 Analysis of Annual Water Supply for Lunar Colonies

### 4.3.1 Problem Analysis

In order to resolve the issue under discussion, it is first necessary to recognise the necessity of ensuring the availability of water prior to the arrival of the colonists, thus avoiding any risk of water scarcity. Secondly, in order to make an informed decision, it is essential to calculate a table detailing the relationship between water loss, delivery costs, and time required after the lunar colony is established, once the annual water supply for 100,000 settlers has been delivered and they commence living there. Data preprocessing

Based on research into water consumption standards for urban residents prioritising water conservation, we have selected the average value of the secondary consumption ceiling, namely 215 litres per day, as the per capita daily water usage. Given that water has a density of 1 tonne per cubic metre, and 1 cubic metre equals 1,000 litres,

it follows that the annual water requirement for a population of 100,000 can be calculated as  $U_{water} = 7847500$ . The advanced water recycling system on the space station achieves a 90% recovery efficiency. Consequently, the annual volume of water requiring transport for replenishment is  $U_{loss} = 784750$

### 4.3.2 Establishment of a Water Demand Estimation Model

The application of the three transport models from Question 1 (under idealised perfect conditions) yielded the following conclusions:

- **Solution for scenario i**

The time required for mode of transport A is as follows

$$T_a = \frac{U_{loss}}{537000}$$

The following transport costs are required

$$D_a = 1015U_{loss}$$

- **Solution for scenario ii**

The time required for mode of transport B is as follows

$$T_b = \frac{U_{loss}}{(100 \sim 150) \times 7300}$$

The following transport costs are required

$$D_b = 5000U_{loss}$$

- **Solution for scenario iii**

The time required for mode of transport C is as follows

$$\begin{cases} T_c = \max\left\{\frac{M_a}{3f_{ax}}, \frac{M_b}{10f_{bx}}\right\} \\ N_a + N_b = U_{loss} \end{cases}$$

The following transport costs are required

$$D_c = 1015W_a + 5000W_b$$

**The application of the three transport models from Question 2 (in the presence of disturbances) yields the following conclusions**

- **Solution for scenario i**

The time required for mode of transport A is as follows

$$T_a = \frac{U_{loss}}{537000\alpha}$$

The following transport costs are required

$$D_a = 1015U_{loss}$$

- **Solution for scenario ii**

The time required for Transport Method B is

$$T_b = \frac{U_{loss}}{100 \sim 150 \times 7300\beta}$$

The following transport costs are required

$$D_b = 5000U_{loss}$$

- **Solution for scenario iii**

The time required for mode of transport C is as follows:

$$\begin{cases} T_c = \max\left\{\frac{M_a}{3\alpha f_{ax}}, \frac{M_b}{10\beta f_{bx}}\right\} \\ N_a + N_b = U_{loss} \end{cases} \quad (7)$$

The following transport costs are required

$$D_c = 1015W_a + 5000W_b$$

### 4.3.3 Solving the model

Substituting the scenario into all the above equations  $M_{total} = 7847500$ ,  $x = 125$ ,  $\alpha = 1$ ,  $\beta = 1$ .

Table 3: Time cost statistics ( $\alpha = 1$ ,  $\beta = 1$ )

proposal	Delivery time(years)	Delivery cost(\$)
<b>Solution for scenario i</b>	1.46	$7.965 \times 10^8$
<b>Solution for scenario ii</b>	0.87	$3.924 \times 10^9$
<b>Solution for scenario iii</b>	0.55	$2.755 \times 10^9$

Substituting the scenario into all the above equations  $M_{total} = 7847500$ ,  $x = 125$ ,  $\alpha = 0.95$ ,  $\beta = 0.98$ .

Table 4: Time cost statistics ( $\alpha = 0.95$ ,  $\beta = 0.98$ )

proposal	Delivery time(years)	Delivery cost(\$)
<b>Solution for scenario i</b>	1.54	$7.965 \times 10^8$
<b>Solution for scenario ii</b>	0.89	$3.924 \times 10^9$
<b>Solution for scenario iii</b>	0.56	$2.778 \times 10^9$

### 4.3.4 Analysis of Results

In comparison to the transportation of materials during base construction, the proportion of water transport requirements relative to construction needs is reduced. The pressure on water transport within the hybrid model is less significant. Once a lunar water recycling system is established with a recovery efficiency of 90%, and considering only the replenishment of losses, the system can fully accommodate this demand. Relying solely on rocket launch sites incurs higher operational costs, while a space elevator system alone lacks the critical redundancy for uninterrupted life-sustaining supplies. Consequently, the hybrid transport model proves the most stable solution under both ideal conditions and in the presence of disruptive factors. It reliably replenishes water losses within lunar colonies in a timely manner, establishing itself as a dependable transport framework.

## 4.4 Analysis of Environmental Impact Assessment and Minimization Strategies

### 4.4.1 Problem Analysis

In order to assess the environmental impact on Earth of establishing a lunar colony with a population of 100,000, the primary focus is on atmospheric pollution and carbon emissions. These are generated by the transport system during both the construction phase (transporting

100 million tonnes of materials) and the operational phase (transporting approximately 550,000 tonnes of water annually). The question explicitly states that the Galactic Port system "does not generate atmospheric pollution". In contrast, traditional rocket launches produce significant emissions. Therefore, this section first quantitatively compares the environmental impacts of three transport options, then discusses how to modify the original model to minimise environmental impact.

A study of the technical characteristics of the two transport systems reveals their primary environmental impact factors to be as follows:

Rocket fuel combustion produces substantial CO<sub>2</sub>, water vapour, and nitrogen oxides.

Atmospheric pollution is caused by the emission of particulate matter and chemical pollutants during rocket launches.

The energy consumption of space elevator systems is dependent on the energy mix, with the system relying on grid electricity.

In order to compare the environmental impacts of different proposals, the following quantitative framework must be established:

The use of CO<sub>2</sub> equivalents CO<sub>2e</sub> as a unified emissions metric is essential.

The construction phase (transporting 100 million tonnes of building materials) is denoted as  $M_{i1}$ , ( $i \in \{a, b\}$ ), while the operational phase (transporting 784750 tonnes of water annually) is denoted as  $M_{i2}$ , ( $i \in \{a, b\}$ ).

Both emissions intensity per unit transported and total cumulative emissions must be considered.

This analysis is conducted under idealised conditions.

#### 4.4.2 Establishment of a Quantitative Assessment Model

The unit carbon emission intensity of Galaxy Harbour is 0.01tonCO<sub>2e</sub>/KWh

The carbon emissions intensity per rocket unit is 32tonCO<sub>2e</sub>/ton

The transportation of 100 million tonnes of building materials is hereby proposed.

Constraint

$$M_{a1} + M_{b1} = M_{total} \quad Ma1 \geq 0 \quad Mb1 \geq 0$$

Carbon emissions

$$E_c = 0.01 \times M_{A1} + 32 \times M_{B1}$$

Transport 784750 tonnes of water annually.

$$M_{a2} + M_{b2} = 784750 \quad Ma1 \geq 0 \quad Mb1 \geq 0$$

$$E_{cwater} = 0.01 \times M_{A2} + 32 \times M_{B2}$$

Carbon emissions during the construction phase and operational phase

$$E = E_C + E_{cwater} = 0.01 \times (M_{A1} + M_{A2}) + 32 \times (M_{B1} + M_{B2}) \quad (8)$$

#### 4.4.3 Solving the model

Substituting the scenario into all the above equations:  $M_{total} = 100000000$ ,  $x = 125$ ,  $\alpha = 1$ ,  $\beta = 1$ .

Table 5: Question 4 Cost-Time Carbon Emissions ( $\alpha = 1$ ,  $\beta = 1$ )

proposal	Total time (Years)	Total cost (\$)	Total carbon emissions (10,000 tonnes $CO_2e$ )
<b>Solution for scenario i</b>	187.68	1022.97	100.78
<b>Solution for scenario ii</b>	111.98	5039.24	322511.20
<b>Solution for scenario iii</b>	70.14	3538.38	202027.98

Substituting the scenario into all the above equations  $M_{total} = 100000000$ ,  $x = 125$ ,  $\alpha = 0.95$ ,  $\beta = 0.98$ .

Table 6: Cost-Time carbon emissions ( $\alpha = 0.95$ ,  $\beta = 0.98$ )

proposal	Total time (Years)	Total cost (\$)	Total carbon emissions (10,000 tonnes $CO_2e$ )
<b>Solution for scenario i</b>	197.56	1022.97	100.78
<b>Solution for scenario ii</b>	114.27	5039.24	322511.20
<b>Solution for scenario iii</b>	72.40	3567.48	204364.68

#### 4.4.4 Analysis of Results

A thoroughgoing environmental impact analysis indicates that the three transport options differ in cost and time, and also exert markedly distinct effects upon the Earth's ecosystems. When pollution from the space elevator system is defined solely by the value of electricity generated by the global grid, and rocket transport alone generates substantial pollution per launch, incorporating environmental impact into the objective function reveals a solution. By allocating the majority of material transport to the space elevator while reserving rockets for supplementary and time-sensitive shipments, this approach maintains a reasonable construction schedule while significantly reducing total emissions. It also ensures the system reliability of life-critical supplies such as water. The hybrid transport strategy proves not only economically and temporally optimal, but also environmentally superior.

## 5 Model validation

### 5.1 Sensitivity Analysis

In order to validate the robustness of the model and the reliability of its conclusions, a sensitivity analysis was conducted. This analysis involved systematically varying the payload capacity for each rocket launch, in order to observe its impact on transport costs, time requirements, and the selection of optimal solutions.

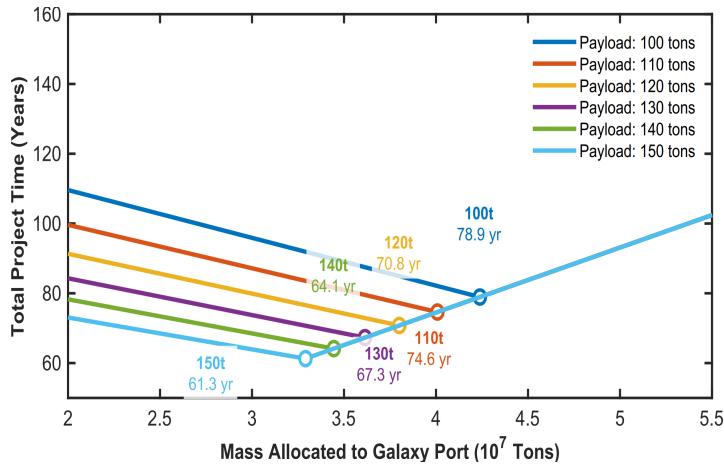


Figure 6: The effect of load variation on time

A sensitivity analysis of varying payload capacity is hereby presented. As demonstrated in the accompanying figure, the discrete enumeration search algorithm, when utilised with a load range of (100–150) and a load increment of 10, establishes a correlation between the duration of Scenario C’s transport and the respective tonnage allocated to each transport method. This analysis substantiates that the shortest transport duration is attained when both methods commence and conclude concurrently, with the associated cost falling between the costs incurred when either method is employed independently. When incorporating time costs, the hybrid transport approach still yields the optimal outcome, thereby demonstrating the model’s soundness.

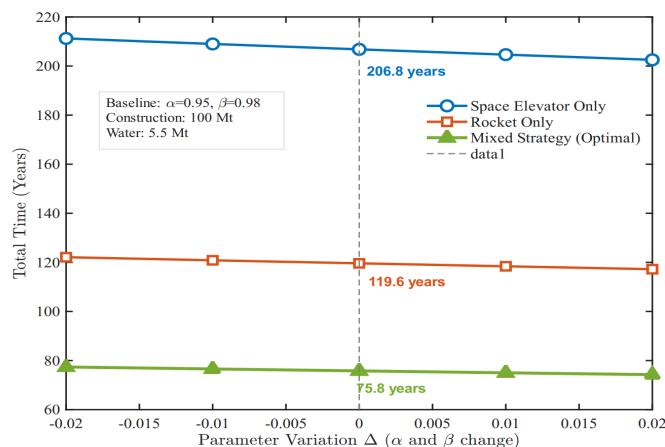


Figure 7: The efect of disturbance coefficients on transport time

A sensitivity analysis of disturbance coefficients was conducted, with particular reference

to the availability of the Galaxy Port System and the rocket launch success rate. To this end, values for alpha and beta were selected, ranging from the assumed values of 0.95 and 0.98, respectively. These values were incremented and decremented in steps of 0.01 on two occasions. It was observed that this factor influenced specific transport times; however, the overall trend remained unaltered.

## 5.2 Error Analysis

Errors arising from the frequency of rocket launches

The frequency of rocket launches assumed in this study is based on the uniformity of global rocket launch capabilities, thus disregarding geographical location. This assumption introduces an error relative to actual conditions. While this error may have a significant impact, under the premise of considering only time costs, the hybrid transport model still achieves the shortest duration. Although numerical results may exhibit deviations due to modelling simplifications, the relative advantage of the hybrid transport strategy remains unaffected.

Cost-related discrepancies

The actual transport costs of space elevator technology remain unknown at present, being based solely on theoretical projections. Furthermore, the calculation of rocket launch costs is derived from the per-kilogram cost of launching rockets into low Earth orbit. Nevertheless, the fact that space elevator technology's transport costs are lower than those of rocket-only transport remains unchanged, and the relative advantages of hybrid transport strategies remain unaffected.

# 6 Model evaluation and optimization

## 6.1 Advantages of the model

Possesses versatility:

The established hybrid transport model has been shown to address a range of problems across multiple scenarios. This demonstrates its universality as a parameterised and transferable framework applicable beyond the specific assumptions of this particular problem to diverse transport contexts.

Its robustness under parameter variations and scalability for different types of supply-demand scenarios (construction materials, water, life support resources) attests to its engineering versatility.

The algorithmic fusion achieves high efficiency while balancing precision and performance:

the model does not confine itself to a single algorithm, but instead constructs a hybrid algorithmic framework that successfully integrates the global optimisation capabilities of the particle swarm algorithm, the precision of enumerative methods, and the phased decision-making advantages of dynamic programming.

## 6.2 Limitations of the model

The cost model is overly simplistic in its approach:

It assumes that the costs of lifts and rockets are fixed values, whereas in reality these costs may vary according to cargo volume, distance, and technological maturity. The model fails to

distinguish between fixed costs (such as lift construction and rocket launch site maintenance) and variable costs.

The model does not take into account variations in launch sites:

The model enumerates ten distinct rocket launch sites, which may differ in geographical location, launch frequency, cost, and payload capacity. However, the model treats them as entirely identical.

The model does not reflect coordination between construction and transport schedules.:

The 100 million tonnes of materials would not be transported in a single shipment. Transport may occur in batches, with construction proceeding concurrently. The time model should be more dynamic.

The reliability coefficients  $\alpha$  and  $\beta$  lack empirical justification. The model extensively employs predictive or hypothetical data.

The model disregards environmental factors such as carbon emissions and energy consumption.

### 6.3 Model optimisation

The following paper sets out the introduction of uncertainty modelling and robust optimisation, as well as stochastic programming. In this section, critical uncertain parameters (e.g. rocket transport costs, per capita water consumption) are modelled as random variables, with optimisation targeting the shortest time.

The subsequent section reintroduces robust optimisation by defining fluctuation ranges for uncertain parameters. This is done in order to seek a robust solution that maintains acceptable performance under all worst-case scenarios. For instance, a strategy may be optimised so that transport time remains below a specified threshold even when parameters fluctuate within  $\pm 5\%$ .

## 7 Correspondence

Theme: Proposal for a Sustainable, Phased Logistics Strategy for Lunar Colonization

To MCM:

The establishment of a lunar colony comprising 100,000 worth of inhabitants presents a considerable logistical challenge. The construction phase alone necessitates the transportation of 100 million worth of materials to the Moon, thereby placing a significant burden on Earth. The subsequent long-term operational phase is even more demanding; according to the model utilised, the annual water consumption exceeds 7,847,500 tons. Even assuming a 90% recycling rate, 784,750 tons of makeup water must be transported annually (approximately 2,150 tons per day). When accounting for other essential living supplies, the total transport volume will be considerably higher.

Core Data Comparison: Environmental Feasibility Analysis Based on IEA 2050 grid projections and physical modelling, we compared the carbon intensity of two transport methods:

**Conventional rockets:** Approximately 32 tonnes  $CO_2$  / tonne payload  
**Galaxy Port System:** Approximately 0.01 tonnes  $CO_2$  / tonne payload

**Galaxy Port System:** Approximately 0.01 tonnes  $CO_2$  / tonne payload

This represents a three-order-of-magnitude difference. The Galaxy Port System, powered electrically, will see its environmental advantages further amplified by advancements in power generation technology. It stands as the sole solution offering long-term economic and environmental sustainability.

Based on these findings, we propose the following **Three-Phase Action Plan**. This plan aligns with current technology readiness, provides sufficient construction time for the space elevator, and achieves a gradual, realistic transition:

**Phase I: Early Construction Phase.** Given that rocket technology is mature, flexible, and immediately available, rockets will serve as the primary transport mode in this phase. The focus is on transporting foundational infrastructure and equipment to establish the initial lunar base.

**Phase II: Transitional Phase.** As construction demands grow, a hybrid strategy should be adopted. Rockets—offering speed and flexibility—will continue to handle urgent and special missions. Meanwhile, the Galaxy Port system will begin to assume responsibility for the bulk of material transport, significantly reducing carbon emissions.

**Phase III: Long-Term Operation Phase.** Once the colony is operational and requires continuous high-volume resupply, the Galaxy Port system should become the main logistical pillar. Its electric drive, extremely low carbon intensity, and suitability for continuous transport make it the only viable long-term solution, conducive to achieving the Net Zero goal.

These three phases ensure short-term feasibility, long-term sustainability, and alignment with global decarbonization targets. This represents the optimal action plan for establishing and maintaining a 100,000-person lunar colony. Therefore, we strongly urge the MCM to adopt this phased transport strategy and prioritize the development of the Galaxy Port system as a core component of future Earth-Moon infrastructure planning.

Sincerely yours,  
Your friends

## References

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- [4] Ishimatsu T, de Weck O L, Hoffman J A, et al. Generalized Multi-Commodity Network Flow Model for the Space Supply Chain[J]. Reston, VA: Journal of Spacecraft and Rockets, 2016.
- [5] SpaceX. Falcon Heavy Users Guide (Revision 3.0)[M]. Hawthorne, CA: Space Exploration Technologies Corp., 2023.

### **Report on use of AI**

1. OpenAI *ChatGPT* (Feb 2026 version, GPT-4o)

Query1: <*Is it necessary to acknowledge the use of translation tools?*>

Output: <*Generally, no. The use of pure translation tools (e.g., Google Translate, DeepL) for converting text from one language to another typically does not need to be formally acknowledged in reports or submissions. This is because they are considered aids for language comprehension rather than tools that generate original ideas, content, code, or solutions.*>

2. DeepSeek-AI *DeepSeek* (Web Version, Feb 2026, DeepSeek-V3)

Query1: <*Please help me analyze question four.*>

Output: <*The core of Question four lies in assessing the impact of different transportation schemes (only space elevators, only traditional rockets, or a combination of both) on the Earth's environment, and proposing model optimization ideas to minimize this impact.*>

Adopted: <*The impact of different factors on the Earth's environment*>

3. DeepSeek-AI *DeepSeek* (Web Version, Feb 2026, DeepSeek-V3)

Query1: <*What papers can be found on the availability of space elevators?*>

Output: <*To search for research materials related to the usability of space elevators, you can conduct a search in Chinese literature databases. A direct and effective method is: visit China National Knowledge Infrastructure (CNKI) and search with the following keywords: Space elevator Track elevator*>