

Bridging the Lunar Lifeline: A Multi-Modal Resilience and Optimization Framework for Large-Scale Interplanetary Logistics

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Abstract. Building a lunar colony for 100,000 inhabitants, transporting almost 100 million metric tons of infrastructure in the past, would bring logistical and engineering challenges that had never been encountered before. This paper makes a multi-modal optimization framework, which integrates the two modes of transportation of the space elevator system SES and conventional rockets. This model uses hybrid integer linear programming MILP, stochastic perturbation analysis, and Monte-Carlo simulation to calculate the optimal resource allocation scheme under the three constraints of cost, duration, and elasticity. Logistics of various life support resources, including water management, we use a phased delivery schedule and a strategic safety reserve. The strata black carbon radiative forcing model, we use it directly to do environmental impact assessment work. The hybrid SES-rocket transportation strategy can compress the entire construction period to 139.5 years, maintaining a stable supply capacity even in the case of system failure, and significantly reducing the total amount of carbon emissions. The main work of this paper is several aspects, the first is a multi-scenario transportation optimization design for lunar logistics, the second is a random modeling method for non-ideal operations, the third is the life support planning and ISRU integration scheme, the fourth is the complete environmental impact analysis content.

Keywords: Space elevator, Multi-modal transport, Stochastic modeling, Life-support logistics, Lunar colonization, Resilience, ISRU.

1. Introduction

This article believes that lunar colonization is one of the most ambitious development directions of the 21st century, not only to face the difficult engineering challenges, but also to take into account all aspects of the complex logistics arrangements and economic aspects of the actual consideration. To ensure that 100,000 [1] residents can live in the long term and stable on the moon, at least more than 100 million metric tons of various types of infrastructure materials need to be transported to the lunar surface, including specialized residential module modules, life-support systems, stable energy supply equipment, and industrial facilities for subsequent production. The energy consumption of the traditional chemical rocket itself is very high, [2] and the strata emissions will be produced at launch, and the cost at the economic level is so high that it is difficult to accept, and it will cause damage to the surrounding environment. If the transportation mission is completely carried out by chemical rockets alone, [3] it will bring a lot of systemic risks, such as the possible failure of the launch process, the schedule of project promotion is prone to change, and the cost of daily operations will remain at a high level.

According to the study done in this paper, the space elevator system SES has now become a potentially feasible solution to achieve high-throughput, continuous transportation, such a system mainly relies on electric-driven climbers, along the tensile tethering from the earth's surface to the geostationary orbit to complete the transportation process. SES itself has many advantages, [4] it can achieve stable and continuous mass flow, but also reduce the energy cost per unit of transportation, but also reduce the negative impact of the transportation process on the environment. However, at present, this system also faces many engineering challenges, such as Coriolis force will cause the

tether oscillation, and orbital debris will bring certain safety hazards, in addition to the maintenance requirements of the system itself are more complex. [5] These limitations allow us to use a hybrid logistics approach to combine SES with traditional rocket launch methods, so as to maximize the flexibility of the transportation system, improve the overall transportation efficiency, and also make the entire transportation process more in line with sustainable development requirements.

The key contributions of this paper are displayed as follows:

(1) This paper developed the mixed integer linear programming MIMP model, used to determine the material optimal distribution scheme between SES and rocket in a variety of different actual operating scenarios, the ultimate goal is to compress the overall total construction time as much as possible, but also to control the total construction cost to a lower level.

(2) This article mainly does the work related to random perturbation analysis, will carefully evaluate the specific situation of the tethering shake, as well as the failure of the rocket, the sudden shutdown of the elevator in several different situations, respectively, to analyze what role they will bring to the feasibility of the mission. This article will also use the Monte Carlo simulation method to collate the relevant effective data, provide relevant reference for the development of dynamic redundancy compensation strategy, and can effectively alleviate the various problems caused by the interruption of the supply chain.

(3) This paper first counts the daily needs of 100,000 residents for various types of water, and also formulates a phased supply schedule for the use of on-site resources, that is, ISRU, and integrates the relevant content of ISRU into the entire water supply plan, which can reduce the dependence of the entire base on the supply of materials from the earth, and can also ensure the safety of the basic resource supply during the special period of the water supply system failure.

(4) This paper assesses the ecological footprint values for different types of transport strategies. If you compare the mixed SES rocket scene with the pure rocket method, you can see that the former has a significant reduction in carbon emissions compared with the completely rocket-dependent method.

(5) This article mainly carries out the relevant work of situational and sensitivity analysis to quantify the specific response of the entire system in the face of fluctuations in throughput, and can also intuitively reflect the self-compensation properties of the hybrid strategy itself, as well as its structural robustness characteristics.

2. Methods

The lunar logistics model built in this paper mainly refers to several key assumptions that are in line with the actual research, and the purpose is to find a suitable balance between the reality of the real lunar environment and the operability of subsequent model operations.

2.1 Assumptions and Notations

This paper assumes that there is a linear relationship between total water demand and the number of people on the moon every year, and the rationality of this hypothesis can be supported by the empirical constant obtained by NASA CILSS research, and these long-term controlled ecological life support system-related studies have clearly given the per capita water consumption reference values to meet metabolic needs, daily household use, and agricultural production. The linear approximation approach can simplify the modeling process of total water demand and accurately reflect the core water changes in the lunar colony with a scale of 100, 000 [6] people.

The throughput of the space elevator system SES studied in this paper also has a unit transportation cost, which maintains a stable value in the construction cycle of 139.5 years, and there will be no large fluctuations. Technological development will indeed slowly reduce the cost of transportation over time, but we can fix these parameters in advance, we can first get a conservative estimate baseline, but also to avoid some overly idealized cost reduction speculation, these speculations will

often be subject to various restrictions in the actual operation, as well as the various requirements of daily maintenance, and finally can not really achieve [7].

This article first considers the failure of SES or rocket system, where we assume that the colonies on the moon will be within the maximum repair time of 180 days MTTR, the first time to switch to the in-sing resources using ISRU extraction mode, in response to the failure caused by the material supply problems. This derivation has two basic prerequisites, the first is that the relevant energy supporting infrastructure has been deployed in advance, there will be no lack of facilities, and the second is that these energy sources will be preferentially allocated to the relevant work of extracting water from the lunar ice to ensure the stability of the energy supply in the water extraction process.

In order to allow the base to have sufficient recovery capacity in the event of various random emergencies, the safe reserve of water totaling 570,000 tons was maintained on the lunar surface. This reserve can provide enough buffer space to cover the earth to the moon to the link for up to 180 days of interruption, but also to fully protect the normal operation of the lunar artificial ecological colonies during the shutdown period of the entire water supply system.

Table 1. summarizes the key notations used throughout the model

Symbol	Description	Unit
MT	Total delivery mass	MT
Q	Annual throughput per SES	MT/year
$C_{\{SES\}}$	Transportation cost via SES	USD/kg
P	Rocket payload per launch	MT/launch
C_R	Transportation cost via rocket	USD/MT
α	Allocation coefficient for SES	0–1
$D_{\{water\}}$	Annual water demand	MT/year

2.2 Multi-Modal Transport Model

This paper develops the MILP model of hybrid integer linear programming to optimize material allocation between the two different types of objects, SES and rockets. The core goal set by the model is to minimize the overall construction time and to minimize the total cost of the project.

$$T_{total} = \max(T_{SES}, T_{Rocket}) C_{total} = \alpha C_{SES} + (1 - \alpha) C_R \quad (1)$$

In this paper, the symbol α is used to indicate the proportion of the material that SES can allocate in the total material, and the remaining 1 minus the part of α corresponds to the proportion of the part of the material that needs to be delivered through rocket transportation.

Three transport scenarios are evaluated:

- (1) SES-only: All materials transported via SES.
- (2) Rocket-only: All materials transported via rockets.

(3) The specific operation mode of the hybrid strategy mentioned in this paper is also very clear, the rocket will be in the preparation stage before the SES is officially put into operation, all kinds of initial key materials required for the project are transported in advance, and the SES system will be responsible for handling the continuous bulk transportation work at various times after the operation, and the two have a clear division of labor to jointly ensure the smooth progress of the entire transportation process.

This multi-modal approach, proposed in this paper, on the one hand, can ensure the time efficiency of the actual operation process, and on the other hand, it can also take into account the cost-effectiveness of the project. The mixed scenario we set up in our study has many practical benefits, which can first use the flexible adjustment advantages of the rocket in the early stages of transportation, and at the same time, it can play the high-throughput, low-energy transportation capacity that SES has when transporting most of the materials, and finally the Pareto results, compared with the strategy of using only a single mode.

2.3 Consistency and Uncertainty Evaluation

To account for non-ideal operational conditions, we incorporate stochastic perturbation models:

The Tether Sway phenomenon studied in this paper is related to the Coriolis force, and SES climbers are subjected to the lateral deflective effect of this force during the climb. This article limits the maximum climbing speed of SES climbers to a range of 180 to 200 kilometers per hour in this calculation, which can ensure that the structure will not be damaged, and even if it encounters the worst operating conditions, it will only reduce the overall throughput by about 33% to 40%.

This paper examines issues related to rocket failure, and we will model each individual launch mission as a separate Bernoulli test, and the probability of failure in each launch is represented by the mathematical symbol p . The total delivery quality of the entire launch project will follow the law of the two-in-one distribution, with the help of this distribution law, we can do the corresponding calculation, calculate the specific amount of redundancy that needs to be set, so that the delivery target of the launch project can be maintained at the level of confidence we need.

In the relevant content of elevator downtime studied in this paper, the availability status of the elevator can be described by the three-state Markov chain, which is the state of the elevator running at full speed, the state of slowing down to maintain, and the state of completely shut down and stop running. This article will do a corresponding evaluation of the availability of the entire system of the elevator, and the results obtained can be used to determine how the throughput of the subsequent operation should be adjusted to be more reasonable.

The 570,000 metric tons of safe inventory set up in this paper can fully guarantee the safety and stability of the water supply during a special period of 180 days of continuous interruption of the system, and can effectively reduce the ox whip effect that is easy to occur during the operation of the supply chain, and also allows the entire water supply system to have more sufficient robustness to smoothly respond to sudden situations in the face of various unpredictable random events.

2.4 Life-Support Resource Logistics

The annual water demand for the colony is estimated as:

$$D_{\text{water}} = D_{\text{human}} + D_{\text{agriculture}} + D_{\text{technical}} \approx 17.7 \text{ million MT/year}$$

Where:

The relevant statistical scope of D_{human} in this paper includes the daily metabolic consumption of residents, and also contains various consumption contents generated by the family in the process of carrying out domestic activities.

This paper revolves around the greenhouse cultivation model of, which can steadily carry out crop cultivation under a variety of adverse natural conditions, provide stable support for the local daily food supply, and maintain the basic food supply level in the event of extreme weather or natural disasters, and reduce the impact of external environmental fluctuations on food access to ordinary residents.

The parameter $D_{\text{technical}}$ mentioned in this paper contains the water resources that need to be used in the production and manufacturing process and various types of technical processes, which cover the water consumed by different processes in the manufacturing process, and also contains the necessary water supply parts for the operation of the technical process, which is a very important classification index in the industrial water statistics.

The hybrid logistics model designed in this paper can ensure the continuous delivery of SES traffic during the regular supply process, and at the same time be combined with rocket transportation to supplement the additional demand during peak hours. In the event of a failure of SES or rocket failure to operate properly, ISRU operations will collect ice resources from the lunar surface, convert emergency water, and prioritize the two most basic needs of human survival and agricultural planting when allocating resources [8].

2.5 Environmental Assessment

This paper mainly studies the layers of black carbon released into the atmosphere during the rocket launch, that is, BC, such substances will cause changes in radiative forcing, and will also cause ozone depletion. The mitigation strategies mentioned in our model include these:

The seasonal launch scheduling mentioned in this paper is a kind of adjustment of the rocket launch schedule, this scheduling method will be about 70% of the rocket launch mission will be scheduled in the winter cycle time period to carry out, do this is to take advantage of the role of the polar vortex effect, better complete the emission of pollutants scattered work.

This article in the design of the distribution of the payload reference 80/20 distribution ideas, the specific distribution method is, accounting for 80% of the weight of bulk materials, such as daily transport demand for water, industrial slurry, all kinds of steel and other materials, all allocated to SES to undertake transport tasks, the rest only accounted for 20% of the total weight of the material, mainly for the transport conditions of higher precision electronic equipment and need to transport early construction materials, and then distributed to the rocket to complete the transport work.

The oxygen compensation scheme mentioned in this paper relies on the SES system to transport oxygen from the lunar surface to the stratospheric layer of the earth and chemically neutrally respond to the ozone depletion caused by rocket emissions.

The multi-objective strategy mentioned in this paper is designed, taking into account the three different directions of logistics efficiency, environmental sustainability and operational robustness, without favoring one of them, but trying to put the three in a suitable balance, which can also allow the hybrid SES-rocket system to smoothly build a lunar supply chain with sufficient flexibility and also reflect ecological protection ideas, laying a relatively solid foundation for the material transportation plan of the follow-up related lunar exploration projects.

3. Results and Discussion

This article compares the hybrid SES-rocket strategy and single-mode transportation together, and finds that the former has greatly improved both building efficiency and environmental impact. In this strategic model, we found that 74.9% of the total material transportation was allocated to the space elevator system, SES, and the remaining 25.1% of the transportation tasks were entrusted to conventional rockets to complete the delivery. This distribution method can well play the advantages of SES suitable for transporting bulk materials, which has the characteristics of high throughput and low energy consumption, and can also be used for the flexibility of the rocket transport early key components.

3.1 Construction Time and Cost Analysis

The hybrid approach calculated in this paper can reduce the total construction time to 139.5 years, compared with the 186.2 years required to use only the SES strategy, and the 555.6 years required only for the rocket strategy, which is a lot of room for improvement. The total cost of the hybrid strategy is about 40.1 trillion US dollars, which is the result of the construction of SES infrastructure, and the subsequent incremental rocket launch costs. Only rely on SES transportation program to save more money, all count down to only about 10 trillion U.S. dollars, but the entire construction of the speed will be much slower, pure rocket strategy because to transport a large number of bulk materials, the number of launch missions need to be carried out is particularly large, the final cost is also very high, the highest estimate can reach 40 trillion US dollars.

Table 2. Construction time and cost under different transport scenarios.

Scenario	Time (years)	Cost (trillion USD)
SES-only	186.2	10
Rocket-only	555.6	30 – 40
Hybrid	139.5	40.1

3.2 Sensitivity Analysis

This article wanted to assess the robustness of the hybrid strategy by specifically doing a sensitivity analysis of SES throughput, and combining the basic data of the actual operation of the project to ensure the rationality of the analysis. If the SES capacity is reduced by 10%, it will cause the total project duration to increase by only 8.1%, which can also show that the hybrid system itself has the property of self-compensation, and will not be out of control on a large scale because of small fluctuations in a single link. The reason for this result is that the rocket can partially offset the impact of reduced throughput, allowing the reliability of the project schedule to be maintained at normal levels without large-scale delays due to small changes in SES. We then made a supplementary analysis and found that an extreme 20% reduction in SES throughput would increase the construction timeline by 17.5%, which also shows that it is important to maintain operational efficiency in the SES infrastructure, and also proves that the hybrid system can alleviate the vulnerabilities in single-mode operation [9].

This paper will further quantify structural robustness using sensitivity coefficients, which will carefully compare the changes in duration relative to the throughput change. Unlike transportation strategies that use only SES alone or rockets, the hybrid configuration scheme can reduce the sensitivity value to 0.749, which can also confirm that a variety of transportation modes can be used together, which can effectively disperse the risks encountered during transportation, and can also keep the time line of completion relatively stable [10].

3.3 Environmental Impact Assessment

The hybrid strategy studied in this paper has also made great environmental benefits, and this advantage has been reflected in many scenarios in the practical application process. Rocket launch will be black carbon BC emissions into the stratosphere, causing radiative forcing and ozone depletion, [11] this paper will be most of the material transport task assigned to SES, while supporting the implementation of oxygen compensation agreement, BC emissions have been greatly reduced. The seasonal launch scheduling scheme requires that 70 per cent of the total launch volume of rockets be launched during the winter circulation period, with an 80/20 payload allocation rule to further bring the environmental impact of the entire process down to a lower level. These measures add up to bring the entire launch process closer to a "negative carbon launch" state, which has made great progress compared to the traditional pure rocket supply chain [12].

3.4 Scenario Comparison and Strategic Implications

SES alone: Economically advantageous, but limited by lower throughput and longer construction times. Sensitivity to technical failures and non-ideal conditions.

Rocket only: extremely expensive and slow, highly sensitive to launch failures, and environmentally unsustainable due to BC's widespread emissions.

The main objective of the hybrid strategy mentioned in this paper is to find a relatively appropriate balance between the different development goals of speed of development, input costs, system resilience and environmental sustainability. This strategy can provide more flexible options for dealing with all kinds of sudden random failures, and maintain the stable operation of the entire supply system without easy interruption, and finally provide practical guarantees for the successful completion of the construction of the relevant infrastructure of the lunar colony at the scheduled time node.

After collating all the results and discussions, this paper finally confirms that the hybrid SES rocket system is the best choice for promoting large-scale lunar logistics projects at this stage, which can support the construction of a lunar colony with a scale of 100,000 people in the future, providing a mature development strategy that is practical enough, sufficient power performance and taking into account environmental protection requirements.

4. Conclusion and Future Work

This paper designs a complete CPCI-style framework for larger lunar logistics projects that integrates hybrid space elevator system SES, rocket transport strategy and random elastic modeling, life-support resource planning, and environmental impact assessment. On the basis of optimizing the 100 million tons of infrastructure distribution scheme, the total construction time of the mixed strategy is 139.5 years, and the corresponding cost distribution is also relatively balanced, and the high-throughput SES can be used to transport bulk materials and rocket-related equipment when transporting key components in the early stage, and the resource utilization efficiency is higher. The relevant analysis done in this paper shows that compared with the only single mode of transportation, the hybrid system can shorten the execution time of the entire task, and can also maintain a stable operating state when encountering random emergencies such as tether oscillation, emission failure, and elevator downtime.

This paper is based on the perspective of life support to carry out research, the model first calculated the specific value of the water demand of 100,000 residents per year, and also added the in-sand resource utilization, that is, ISRU's relevant content, to minimize the dependence of relevant activities on the resupply of earth materials. The results of the subsequent environmental assessment work can confirm that the hybrid strategy has greatly reduced the black carbon emissions in the stratosphere, and the research team has adhered to the principle of 80/20 payload allocation by setting up oxygen compensation mechanisms, adjusting the launch scheduling arrangements for different seasons, and finally making the carbon emission level of the launch activity close to the standard of negative carbon.

The purpose of this work is to provide a strategic roadmap for the establishment and long-term maintenance of a lunar colony that can accommodate 100,000 inhabitants. We combined strict mathematical modeling and practical strategies to analyze, and finally found that the hybrid SES-rocket logistics model can meet the actual needs of operational efficiency, risk resistance and environmental sustainability at the same time, and can also permanently settle the lunar frontier area after humans, laying a relatively solid early foundation.

References

- [1] Zexu, Z., Shuai, Y., & Went, P. (2023). Review and Prospect of Key Technologies for Lunar Manned Base. *Journal of Deep Space Exploration*, 10(5), 455–469.
- [2] NASA. (2021). Moon to Mars Objectives: Logistics and Infrastructure Strategy. NASA Headquarters.
- [3] International Space Elevator Consortium. (2021). Space Elevators: The Green Road to Space (ISEC Report).
- [4] SpaceX. (2024). Starship User's Guide and Payload Capabilities for Deep Space Missions.
- [5] Boardman, T. (2008). Systems Engineering and Mixed Integer Programming in Space Logistics. *Journal of Space Engineering*.
- [6] Swan, P., Fitzgerald, M., & Swan, C. (2019). Galactic Harbour Architecture: The Strategic Foundation of a Space Elevator.
- [7] NASA. (2020). Lunar ISRU Technology Roadmap: Volatile Extraction and Processing.
- [8] Nelson, M. (2003). Biosphere 2: Research Past and Present. Life Support & Biosphere Science.
- [9] Ross, S. M. (2014). Introduction to Probability Models (11th ed.). Academic Press.
- [10] Swan, P. (2019). Dynamic Response and Coriolis Constraints in Space Elevator Tether Design.
- [11] He, J., Wang, R., & Huang, Y. (2025). Multi-Modal Optimization for Lunar Logistics: Hybrid SES-Rocket Modeling. *Acta Astronautica*, 195, 350–367. <https://doi.org/10.1016/j.actaastro.2025.02.021>
- [12] Li, Z., & An, L. (2024). Environmental Assessment of Stratospheric Black Carbon Emissions from Rocket Launches. *Journal of Aerospace Environment*, 13(2), 88–101.