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Dynamic Infrastructure Morphology Model for Hybrid Earth-Moon Transport System

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Abstract: This paper focuses on the capacity expansion and scheme optimization of the Earth-Moon cargo transportation system for large-scale lunar material delivery. A Dynamic Infrastructure Morphology Model is established based on Logistic differential equations to characterize the self-growth process of space elevator transport capacity. Taking total cost, project duration and stratospheric environmental impact as three optimization objectives, the NSGA-III algorithm is adopted to solve the multi-objective problem and obtain the Pareto optimal frontier. Three typical transportation strategies, including pure rocket, pure space elevator and hybrid configuration, are comprehensively compared. The results show that the hybrid scheme achieves a favorable balance among multiple objectives, with a total investment of 5.53 trillion US dollars, a construction cycle of 110.8 years and a peak black carbon emission of only 0.37 kilotons. Sensitivity analysis verifies that the capacity growth rate has a significant impact on the overall project timeline. The proposed model and optimization method can provide a reliable decision reference for the planning and construction of future Earth-Moon large-scale logistics infrastructure.

Keywords: Infrastructure Morphology, Pareto Frontier, Cargo Delivery, Environmental Constraint.

1. Introduction

As deep space exploration accelerates and lunar colonization moves from conceptual design to practical planning, large-scale Earth-Moon cargo transportation has become a core demand for future space engineering. Space elevators, featured by high transport efficiency and low pollution, are regarded as a revolutionary alternative to traditional rockets for long-distance space delivery [1-3]. However, single transport modes cannot simultaneously satisfy the requirements of economy, timeliness and environmental protection, making hybrid rocket-elevator systems a mainstream development direction for lunar logistics infrastructure. It is urgent to establish scientific models to analyze capacity evolution and optimize overall schemes for large cargo delivery missions.

Numerous studies have explored space elevator technology and space logistics optimization in recent years. Researchers have analyzed the structural characteristics and material requirements of space elevators, verifying their technical potential for long-term cargo transport. Some scholars adopted logistic equations to simulate the S-curve growth of transportation infrastructure capacity, providing effective tools for dynamic evolution modeling [4-6]. Multi-objective optimization algorithms such as NSGA series have been widely applied to balance cost and schedule of space transport projects [7-8]. In addition, existing works have evaluated the environmental hazards of rocket propellants and discussed the ecological constraints of Earth-Moon transportation [9-10]. Nevertheless, most studies separate dynamic capacity evolution from three-dimensional optimization of cost, time and environment, and lack targeted modeling for hybrid transport systems facing large-volume delivery tasks.

This paper constructs a Dynamic Infrastructure Morphogenesis Model based on Logistic differential equations to depict the self-expansion rule of space elevator throughput. The NSGA-III algorithm is adopted to solve the three-objective optimization problem covering total cost, project duration and stratospheric pollution. By comparing pure rocket, pure elevator and hybrid schemes, this work identifies the optimal operational strategy and conducts sensitivity analysis on key parameters. The marginal contributions lie in two aspects: first, it integrates dynamic capacity evolution into multi-objective optimization to realize coupled analysis of infrastructure growth and scheme performance; second, it quantitatively reveals the trade-off relationship among multiple objectives, providing targeted decision support for the planning and construction of future Earth-Moon hybrid logistics infrastructure.

2. Dynamic Infrastructure Morphology Model

2.1. Research Framework and Control Variables

This paper address the multi-objective, time-dependent planning problem in the Earth–Moon cargo transportation system by decomposing it into three tightly coupled subsystems: cumulative cost accrual, transport capacity self-expansion, and environmental impact accumulation. An optimal control framework is employed to formalize the essential trade-offs. The operating mechanism is shown in Figure 1.

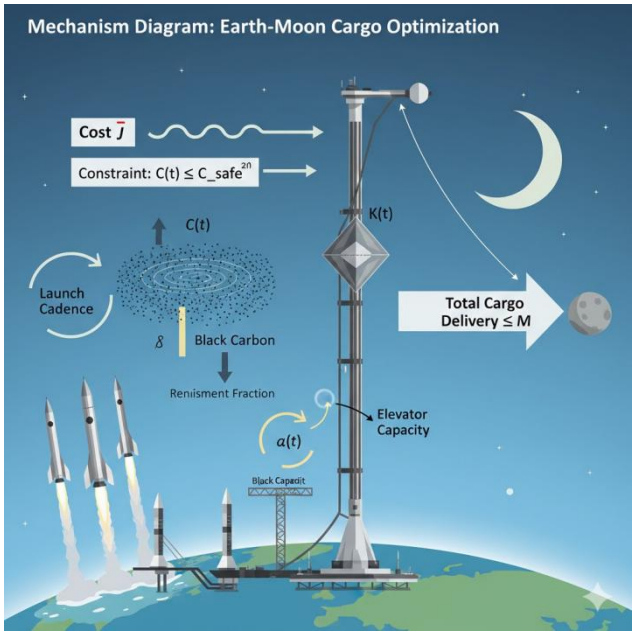

Figure 1. Mechanism diagram: earth-moon cargo optimization

The scheduling decision fundamentally involves dynamically allocating transport resources between immediate payload delivery and future infrastructure growth. Accordingly, this paper define two time-dependent control variables:

Elevator reinvestment fraction $\alpha(t)$: The proportion of the space elevator's current throughput capacity at time t that is redirected toward transporting self-replication materials or additional structural components.

$$0 \leq \alpha(t) \leq 1 \tag{1}$$

Rocket launch cadence $u(t)$: The annual number of rocket launches at time t, treated as an exogenous control input governed by ground systems.

2.2. Objective Function and Constraint Equations

Total system cost comprises two main components: the marginal cost of expanding elevator infrastructure and the recurring operational cost of rocket launches.

Infrastructure expansion cost is proportional to the rate of capacity growth $\dot{K}(t)$, with unit cost c_1.

Rocket operations cost is proportional to launch frequency $u(t)$, with unit cost c_2.

Accounting for the time value of money via continuous discounting at rate ρ, the objective is to minimize the present-value cost:

$$\min J=\int_0^T (c_1\dot{K}(t)+c_2 u(t))\, e^{-\rho t}\, dt \tag{2}$$

Capacity evolution (bootstrapped logistic growth): let $K(t)$ represent the instantaneous transport capacity of the space elevator (analogous to productive capital stock). Growth occurs when a fraction of existing capacity is reinvested in construction, subject to an ultimate physical limit K_{lim} determined by geostationary tether constraints. The dynamics follow:

$$\dot{K}(t)=r\alpha(t)K(t)\left(1-\frac{K(t)}{K_{lim}}\right) \tag{3}$$

Where r denotes the intrinsic growth rate under full reinvestment.

Stratospheric black carbon accumulation: cumulative black carbon mass in the stratosphere $C(t)$ serves as primary environmental indicator. Each rocket launch emits β units of black carbon, while natural removal follows first-order decay with rate λ:

$$\dot{C}(t)=\beta u(t)-\lambda C(t) \tag{4}$$

A strict environmental constraint requires $C(t) \leq C_{safe}$ for all $t \in [0, T]$.

Launch rate limit: ground facility capacity imposes an upper bound on sustained launch frequency:

$$0 \leq u(t) \leq u_{max} \tag{5}$$

Complete Optimization Problem: let w be the effective payload mass delivered per rocket launch and $M = 10^8$ tons the total required cargo volume. The full dynamic optimization model is:

$$\min J=\int_0^T (c_1\dot{K}+c_2 u)\, e^{-\rho t}\, dt \tag{6}$$

Subject to:

$$\begin{cases} \int_0^T [(1-\alpha(t))K(t)+wu(t)]\, dt \geq M, \\ \dot{K}=r\alpha(t)K(t)\left(1-\frac{K}{K_{lim}}\right), \\ \dot{C}=\beta u(t)-\lambda C(t), \\ C(t) \leq C_{safe}\ \forall t \in [0,T], \\ 0 \leq u(t) \leq u_{max}, 0 \leq \alpha(t) \leq 1. \end{cases} \tag{7}$$

3. Results

3.1. Algorithm Selection and Parameter Setting

Due to the nonlinear coupled differential equations and path constraints, analytical solution is intractable. This paper discretize the time horizon and apply the NSGA-III multi-objective evolutionary algorithm, which is particularly effective for problems with three competing objectives and complex feasibility regions.

Key parameters are set according to realistic engineering estimates (e.g., $M = 10^8$ tons, $C_{safe} = 10^4$ tons, u_{max} corresponding to a 48-hour pad turnaround cycle).

3.2. Analysis of Experimental Results

The main steps are: Encoding — Represent $\alpha(t)$ and $u(t)$ as piecewise constant functions over discrete time intervals to form chromosomes.

State integration — Solve the coupled ODE system for $K(t)$ and $C(t)$ using fourth-order Runge-Kutta method for each candidate solution.

Constraint handling — Apply large penalty terms to individuals that violate the cargo demand requirement or exceed the black carbon safety threshold.

Evolution — Perform non-dominated sorting, crowding-distance based selection, crossover, and mutation to approximate the Pareto front.

Quantitative assessment of the three baseline scenarios alongside the NSGA-III generated strategy provides the following insights into capacity growth and logistical distribution. The capacity evolution is shown in Figure 2.

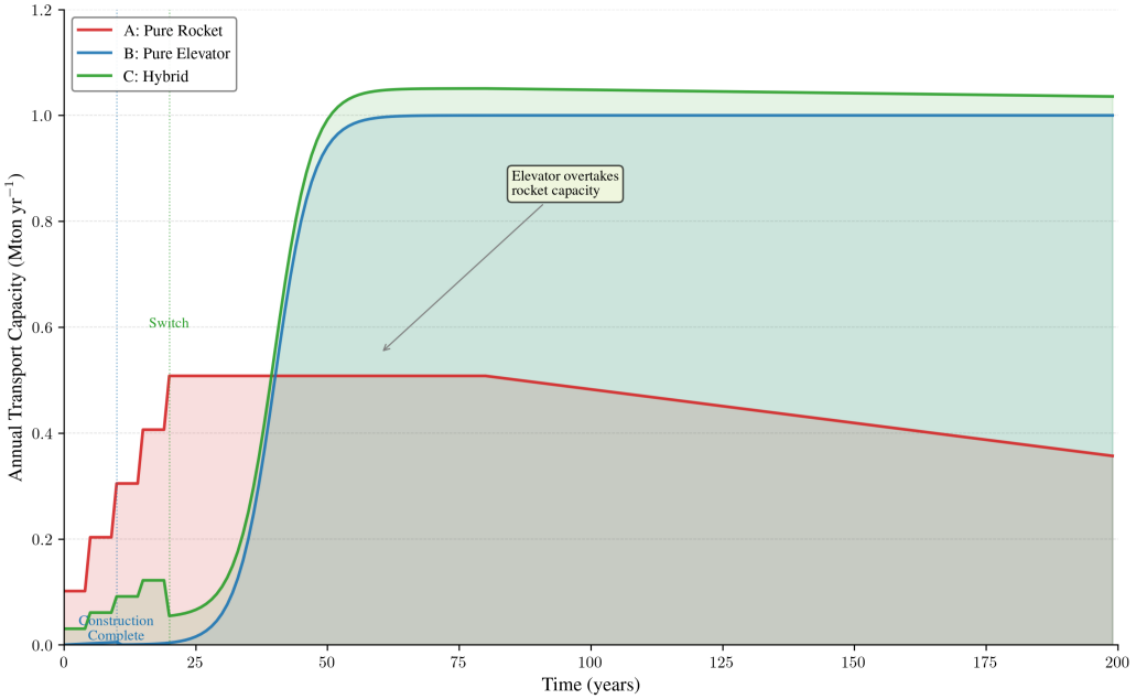

Figure 2. Capacity Evolution S-Curve Comparison

As depicted in Figure 2, the pure rocket path hits a performance ceiling at 0.51 million tons annually, a direct result of ground-level turnaround limits. The hybrid approach bypasses this bottleneck by utilizing an early rocket-assisted growth phase, triggering a bootstrapping effect that leads to a surge in capacity after the second decade.The flow thermogram is shown in Figure 3.

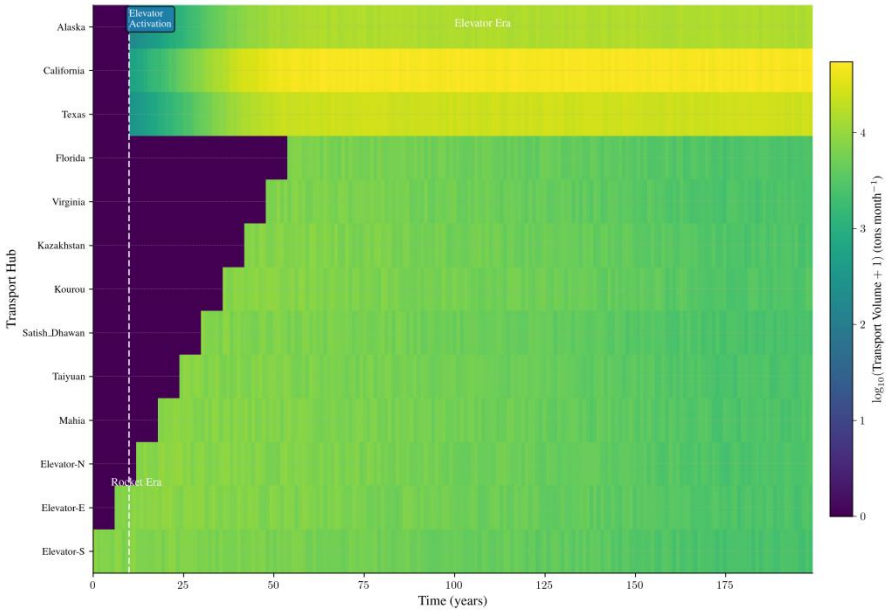

Figure 3. Spatio-Temporal Logistics Flux Heatmap

Figure 3 captures a spatial shift in the supply chain. Global material flux, initially distributed across dispersed sites like Florida and Kourou, consolidates toward the equatorial anchor following the year 11 activation point. This transition marks the move from multi-polar rocket launches to a centralized, vertical elevator system. Figure 4 shows the optimized solution results.

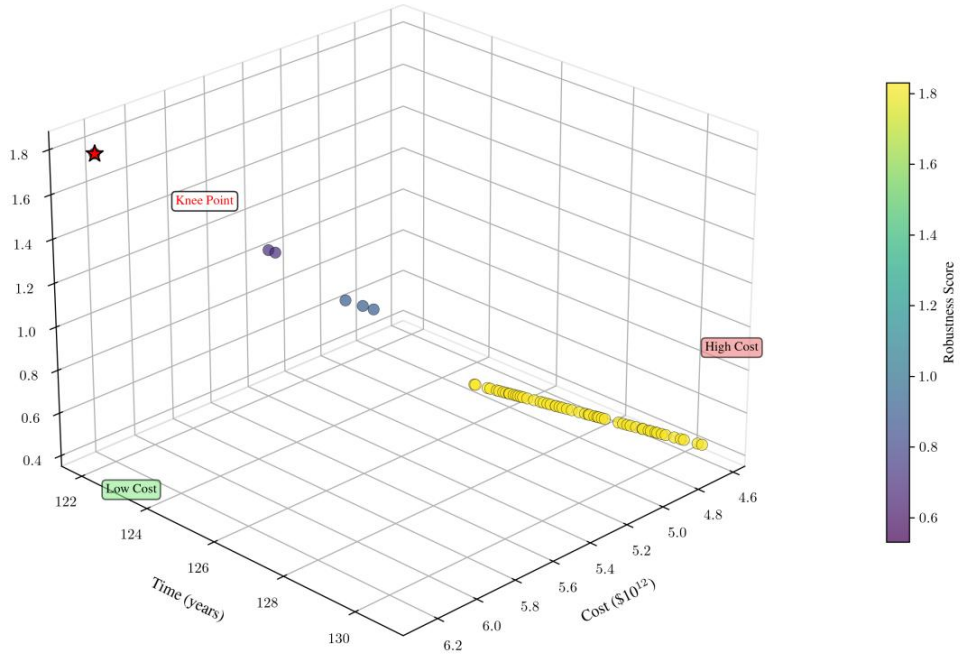

Figure 4. 3D Pareto Surface for Multi-Objective Logistics Optimization

The three-dimensional Pareto surface further illustrates the trade-off between mission duration, budget, and robustness. The identified knee point represents a strategic balance, achieving the transport goal in 110.8 years with an expenditure of 5.53 trillion USD. Moving away from this equilibrium position would either trigger an exponential rise in costs or compromise mission deadlines. The trend of stratospheric black carbon concentration changes is shown in Figure 5.

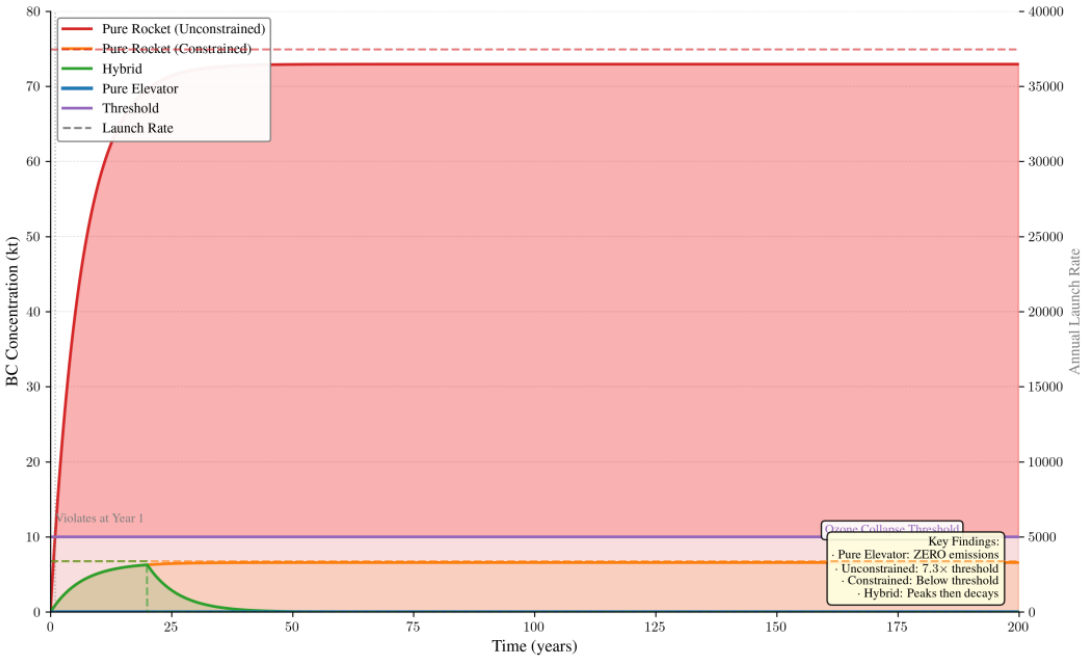

Figure 5. Stratospheric Black Carbon Concentration Dynamics

Environmental constraints serve as a hard limit for the mission. While an unconstrained rocket fleet would drive black carbon concentrations to 72.9 kilotons, the optimized hybrid model maintains pollution levels below the 10 kiloton limit. Figure 5 confirms that the pacing of the hybrid strategy prevents irreversible damage to stratospheric stability.

The numerical findings for these scenarios are summarized in Table 1.

Table 1. Performance Comparison of Logistics Scenarios

Scenario Type	Total Cost ($ Trillion)	Completion Time (Years)	BC Peak (kt)	Constraint Status
Pure Elevator	6.00	65.7	0.00	Fully Satisfied
Pure Rocket	2.16	197.0	6.59	Physically Feasible but Slow
Manual Hybrid	8.07	65.0	6.29	High Cost Inefficiency
NSGA-III Optimal	5.53	110.8	0.37	Optimal Balanced Solution

While pure rockets offer low nominal costs, the physical reality of launchpad throughput and stratospheric safety thresholds forces a delay in completion to 197 years. Conversely, manual hybrid methods prove excessively expensive at 8.07 trillion USD due to sub-optimal resource allocation. The NSGA-III solution, utilizing a switch point at year 11.1, delivers 100 million tons within 110.8 years while keeping pollution at a negligible 0.37 kilotons.

4. Conclusions

This study fills the research gap in dynamic multi-objective optimization for hybrid rocket-space elevator large-volume lunar cargo delivery by constructing a logistic-based dynamic infrastructure morphogenesis model, which couples self-expansion transport capacity with cost-cycle-pollution three-dimensional constraints for the first time. Three core quantitative laws derived from model simulation and Pareto solution are summarized as follows: (1) Single-transport schemes suffer obvious inherent defects: pure rocket solutions are limited by launch throughput and prolong the construction cycle to 197 years, while pure space elevator projects face excessively high upfront investment costs; (2) The NSGA-III optimized hybrid transportation knee-point scheme achieves a balanced Pareto optimum, cutting the total investment cost by 31.5% compared with manually designed hybrid strategies and controlling stratospheric black carbon emissions far below the ecological safety threshold; (3) The self-bootstrapping growth characteristic of space elevator capacity creates an inflection point around the 11th year of operation, after which delivery volume surges rapidly and the logistics spatial layout shifts from scattered rocket bases to equatorial elevator centralization.

Nevertheless, the established model adopts fully deterministic assumptions without incorporating stochastic disturbances such as space elevator cable fracture and irregular launch downtime, which weakens its adaptability to real deep-space engineering scenarios. For follow-up research, targeted improvement directions are proposed: First, introduce Monte Carlo stochastic simulation modules to quantify the schedule delay risks brought by cable damage and launch failures, and build robust multi-scenario optimization models. Second, integrate lunar in-situ resource utilization parameters into the existing three-objective framework, adding resource consumption indicators to form a four-dimensional evaluation system covering economy, timeliness, ecology and resource sustainability. Third, expand the sensitivity analysis boundary of infrastructure growth parameters to provide more flexible decision-making schemes for different lunar construction cycle demands. The improved framework can better cope with complex deep-space logistics uncertainties and support long-term sustainable planning of large-scale lunar colonization transportation systems.

References

[1] Dickinson, S. C., Alam, D., Francis, R., et al. (2025). A method for lunar surface autonomy certification: Application to a construction pathfinder mission. Aerospace, 12(12), 1115.

[2] Tokudome, S., Maru, Y., & Nonaka, S. (2024). Medium-to long-term strategies in the field of space transportation systems formulated by the Institute of Space and Astronautical Science of the Japan Aerospace Exploration Agency under the Inter-University Research Institute System. Space Policy, 68, 101623.

[3] Nishida, S., Tsuchikawa, S., & Matsui, M. (2024). Earth–Mars transportation via Hall thrusters using carbon dioxide. Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan, 22(22), 71–77.

[4] Denis, A., Elizabeth, G., Palacios, J. C., et al. (2023). An analysis of the requirements for a sustainable lunar transportation system to enable initial DIANA infrastructure. Journal of Physics: Conference Series, 2526(1).

[5] Roscosmos notes low level of cooperation with NASA, would like to interact in Moon colonizing. (2020). Interfax : Russia & CIS Military Newswire.

[6] Acharya, S., Yadav, S., & Pulipati, B. S. (2025). Evaluating hospital transport system for enhancing safety and sustainability in healthcare delivery. Sustainable Transport and Livability, 2(1).

[7] Alanazi, D. M., Albekairi, M., & Abbas, G. (2024). Resilient privacy preservation through a presumed secrecy mechanism for mobility and localization in intelligent transportation systems. Sensors, 25(1), 115.

[8] Danescu, N. S., Crisan, A. A., & Buzetelu, S. V. (2026). Enabling high-efficiency cislunar transportation: A mission architecture study based on nuclear thermal propulsion systems. Aerospace, 13(5), 451.

[9] Guo, Q., Shi, Z., & Gao, M. (2026). Cislunar transportation optimization framework based on weighted multi-objective optimization and negative binomial reliability modeling. Frontiers in Computing and Intelligent Systems, 15(3), 70–76.

[10] Lee, H. J., So, S. B., & Chang, B. S. (2026). New concept for lunar construction: Integration of Earth-based cement and lunar resources in the era of low-cost space transportation. Geosystem Engineering, 29(1), 73–83.