

Research on Heterogeneous Transport Capacity Coordination Modeling and Comprehensive Evaluation for Large-Scale Earth-Moon Material Transfer Systems

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Abstract: Addressing the requirement to transport 100 million tons of materials for establishing a 100,000-person lunar settlement by 2050, this paper establishes a quantitative evaluation framework encompassing traditional rocket networks, pure space elevator systems, and hybrid transport solutions integrating both. The study first establishes a dynamic growth model based on technology learning curves, capturing the exponential enhancement of space elevator payload capacity over time. Simultaneously, for traditional rocket networks, a nonlinear decreasing model for per-launch costs with increasing reuse cycles is derived, incorporating reusability technology evolution trends. To achieve optimal allocation of transport resources during long-term construction phases, this study innovatively introduces a sigmoid function as a dynamic allocation weighting mechanism. This enables the system to fully leverage mature rocket technology during the initial construction phase while smoothly transitioning to the high-potential space elevator solution in the later stages. Quantitative evaluation using the Analytic Hierarchy Process (AHP) across two core dimensions—transportation time and comprehensive cost—reveals that the hybrid approach achieves a significantly superior composite score of 0.932 compared to pure rocket and pure elevator solutions. This study not only demonstrates the hybrid transport model's superiority in shortening project cycles and controlling long-term expenditures but also provides a scientific decision-making benchmark for strategic planning of large-scale deep-space logistics systems.

Keywords: Hybrid transport system, Analytic Hierarchy Process, Technology learning curve.

1. Introduction

With the leapfrog development of deep-space exploration technology, establishing permanent lunar colonies has transitioned from scientific concept to engineering practice. However, the requirement to transport up to 100 million tons of construction materials poses extremely stringent challenges to the efficiency, cost, and sustainability of existing space logistics systems.

In the field of logistics and transportation optimization, current research provides a rich theoretical foundation but also reveals certain limitations. Lv J et al. [1] proposed an intelligent multi-level network optimization method for underground transportation systems, providing a computational intelligence perspective for solving complex logistics network problems. Building on advanced computational approaches, Hongming L et al. [2] explored supply chain transportation and route planning based on Deep Reinforcement Learning, offering new ideas for dynamic decision-making in complex environments. In specific transportation scenarios, Saleh H et al. [3] developed a scenario-based approach to drone-based blood supply transportation, addressing critical challenges in specialized medical logistics.

In terms of technological innovation, Wu Y et al. [4] utilized the Whale-Swarm Hybrid Algorithm to optimize UAV material transportation, while Zhang Y et al. [5] studied trajectory tracking control for emergency supplies transportation robots using improved model predictive control. From a flow optimization perspective, Zhou W et al.

[6] proposed an optimal flow distribution model for military supply transportation based on network analysis and entropy measurement, providing valuable insights for strategic logistics planning. Additionally, Tang M et al. [7] investigated yaw stability control for unmanned emergency supplies transportation vehicles, contributing to the safety and reliability of autonomous transportation systems.

Furthermore, research on emergency logistics has yielded significant advances. An J et al. [8] examined transportation and reserve strategies for emergency medical supplies during public health events, while Guang Y et al. [9] applied hallway exploration-inspired guidance to autonomous material transportation in construction sites. In the domain of disaster preparedness, Döyem A et al. [10] developed an integrated disaster preparedness model for retrofitting and relief item transportation.

Despite these advances in terrestrial and emergency logistics, previous space logistics research has predominantly focused on static capacity assessments, often failing to capture dynamic performance gains during technological evolution. This limitation hinders the formulation of optimal transport strategies within complex technological trade-offs. While traditional chemical-propulsion rockets are technologically mature, they incur extremely high economic costs and environmental burdens when handling massive payloads. Space elevators, as a revolutionary alternative, offer extremely low marginal costs and environmental friendliness, but their technological iteration path and initial construction scale remain highly uncertain.

To address this gap, this section innovates by abstracting

space material transfer into a large-scale continuous-flow logistics optimization problem. It employs Wright's technology learning curve to describe emerging technologies' efficiency evolution and integrates a logical allocation function to achieve dynamic coordination between heterogeneous transport capacities. The overall research approach follows a logical progression from single-path mechanism modeling to multi-modal system integration: First, the upper limits of transport capacity and cost evolution for traditional rocket networks and pure space elevator systems are independently calculated. Subsequently, a hybrid solution with dynamically allocated weights is constructed. Finally, the Analytic Hierarchy Process is employed to conduct a comprehensive performance evaluation of each solution under multi-objective constraints, aiming to identify the optimal Earth-Moon logistics evolution path that balances construction progress and financial feasibility.

2. Comprehensive Evaluation of Three Transportation Schemes

2.1. Model Establishment

The transportation of materials for Moon Colony construction can be abstracted as a large-scale continuous-flow logistics system optimization problem. As a breakthrough transportation technology, the Space Elevator System is characterized by three core features: substantial upfront investment but extremely low marginal costs; strong technological scalability with significant performance improvements over time; and minimal environmental externalities, aligning with sustainable development requirements. These features render traditional static logistics models inapplicable, necessitating the construction of a Dynamic Growth Model to capture the critical impacts of technological evolution.

2.1.1. Pure Traditional Rocket Network

As the sole implementation pathway for traditional rocket transportation, the Pure Traditional Rocket Network focuses on maximizing the operational efficiency of existing launch sites, assuming mature and stable rocket technology by 2050. The annual transport capacity of the ten launch sites is determined by multiplying the payload capacity per launch by the annual number of launches, reflecting the total volume of supplies that these ten sites can stably deliver over a year. The calculation formula is as follows:

$$C_r = m \times n_{\text{launch}} \quad (1)$$

where the single-launch payload capacity is $m = 125$ metric tons per launch. To estimate the annual number of launches n_{launch} for 2050, with the average launch and recovery cycle of the current Falcon Heavy rocket being approximately two days as the baseline, the theoretical annual number of launches amounts to approximately 183. Based on the trend that rocket payload capacity witnessed an average annual growth of roughly 4.2% from 1957 to 2020, the annual number of launches n_{launch} is estimated to reach a maximum of around 5,000 launches per year by 2050. When this value is substituted into the formula, the corresponding total annual transport capacity is calculated as 625,000 metric tons.

Since rocket technology growth is not considered, the total transport capacity remains fixed, and the transport process is continuous and stable, the transportation time is the ratio of the total transport demand to the total annual transport capacity. That is:

$$T_r = \frac{Q}{C_{\text{rocket}}} \quad (2)$$

Beyond analyzing transport capacity within the Pure Traditional Rocket Network, cost-effectiveness remains a critical evaluation dimension. Given the maturity of rocket reuse technology, the actual cost per launch will decrease significantly as the number of reuses increases, reaching a minimum by 2050. Based on data from the existing Falcon Heavy rocket, the relationship between their cost and the number of reuses shows a nonlinear pattern of "exponential decline + marginal diminishing", which can be approximated as:

$$B(n) = B_0 \times (0.85)^n + B_{\text{min}} \quad (3)$$

where:

$B(n)$ denotes the marginal cost per launch after n reuses;

B_0 represents the cost of the first reuse, approximately \$28 million;

n is the cumulative number of rocket reuses;

B_{min} represents the cost floor, approximately \$15 million, mainly including the expendable cost of the second stage and fixed operational costs.

Using Python for modeling and computation, it is estimated that by 2050, the per-launch cost of the Falcon Heavy rocket will be around \$15.21 million. Therefore, the total transportation cost over the entire planning period is:

$$\text{Cost}_{\text{rocket,total}} = c_{\text{rocket}} \times \frac{Q}{125} \quad (4)$$

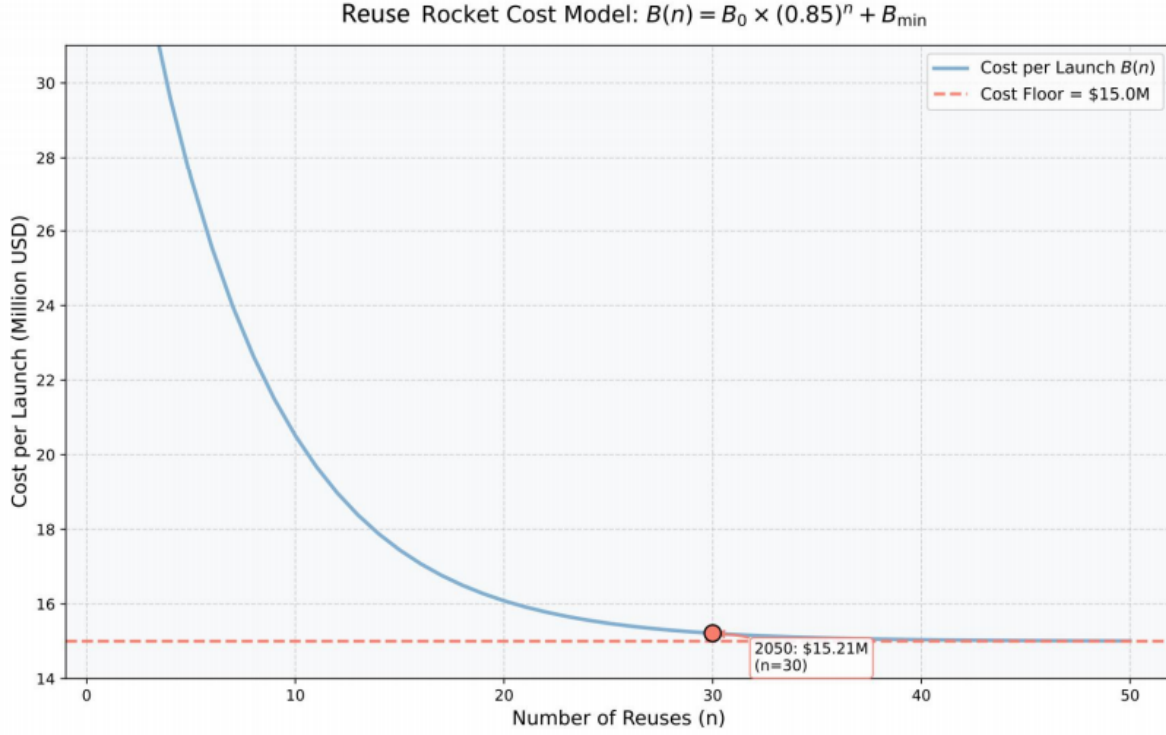


Figure 1: Reuse rocket launch cost vs. reuse count (2050 projection)

Reuse rocket launch cost vs. reuse count are shown in figure 1.

2.1.2. Pure Space Elevator System

In the field of Engineering Economics, performance improvements in emerging technologies typically follow the Technology Learning Curve law. Wright first observed this phenomenon in the aircraft manufacturing industry: each doubling of production volume reduces Unit Cost[2]. This principle was later generalized as:

$$Y(t) = Y_0 \cdot (1 + r)^t \quad (5)$$

where r is the Learning Rate and t represents Time.

For material-driven technologies like space elevators, their performance improvement is mainly driven by two factors: breakthroughs in materials science and control system optimization. Therefore, using an exponential growth model not only aligns with historical experience but also has a solid engineering physics basis.

From 1957 to 2020, the annual average growth rate of rocket carrying capacity was approximately 4.2%. Based on this historical trend, the technical growth rate parameter r of the space elevator is set as follows:

Conservative scenario: $r = 3\%$ (slightly below historical rocket growth); Baseline scenario: $r = 5\%$ (slightly above historical rocket growth); Optimistic scenario: $r = 7\%$ (reflecting moderately optimistic expectations); The baseline scenario (5%) serves as the core basis for calculations.

Let $t = 0$ correspond to 2050 (the year transportation commences). Then, the transport capacity of a single Galactic Harbour (GH) in year $t (t \in \mathbb{Z}^+)$ is:

$$C_e(t) = C_{e0} \cdot (1 + r)^t \quad (6)$$

When $r > 0$, the transport capacity grows exponentially, reflecting continuous technological advancement;

When $r = 0$, the model degenerates into a constant capacity model, serving as the baseline reference;

Three Galactic Harbours (GHs) operate in full coordination, and the Total Transportation Capacity is:

$$C_{e,\text{total}}(t) = N_e \cdot C_e(t) = 3C_{e0}(1 + r)^t \quad (7)$$

Cumulative Transportation Volume is the time integral of Transport Capacity. Since the transport process is continuous, the Transportation Volume in year t is $C_{e,\text{total}}(t)$. The total transportation volume over the first T years is:

$$S(T) = C_{e,\text{total}}(t) = 3C_{e0} \cdot \frac{(1 + r)^T - 1}{r} \quad (8)$$

The condition for completing transport is when the Cumulative Transportation Volume reaches the total demand Q i.e., $S(T) = Q$. Solving for the transport time:

$$T = \frac{\ln\left(1 + \frac{Qr}{3C_{e0}}\right)}{\ln(1 + r)} \quad (9)$$

Given the transporting materials via the Space Elevator System involves two stages: first delivering materials to the spaceport via the elevator, then transferring them to the moon via rockets. Accordingly, the total Unit Transportation Cost can be expressed as: R . Referring to relevant literature, the baseline unit cost of elevator transportation $C_{\text{elevator}0}$ is \$220,000 per metric ton. The elevator transportation cost in the t -th year is then:

$$C_{\text{elevator}}(t) = C_{\text{elevator}0} \cdot (1 + R)^{-t} \quad (10)$$

The annual transportation cost of the Space Elevator System depends on the total Transportation Volume and the Unit Transportation Cost in that year. Let C_{fuel} denote the fuel cost saved by space elevator transportation. Therefore, the total transportation cost over the entire planning period is:

$$\text{Cost}_{e,\text{total}} = 3C_{\text{elevator}0}C_{\text{elevator}0}(1 + r)^t(1 + R)^{-t} \cdot \frac{\ln\left(1 + \frac{Qr}{3C_{\text{elevator},0}}\right)}{\ln(1 + r)} + \frac{Q}{125} \cdot (c_{\text{rocket}} - c_{\text{fuel}}) \quad (11)$$

2.1.3. Hybrid Combination Scheme

The Hybrid Combination Scheme aims to achieve an optimal balance between transportation costs and time by leveraging the respective advantages of the Space Elevator and rocket transportation. In this scenario, simultaneous operation of the Space Elevator and rocket systems is assumed, with mission allocation determined by their dynamic transportation capacities.

Let the amount of cargo transported via the Space Elevator in year t be denoted as $Q_e(t)$, the amount transported via rockets as $Q_r(t)$, and the total annual transport demand allocation as $Q(t)$, which satisfies:

$$Q(t) = Q_e(t) + Q_r(t) \quad (12)$$

The total transportation demand is $Q = 10^8$ metric tons, to be fulfilled within the planning period. The annual transportation capacity of the Space Elevator $C_e(t)$ follows an exponential growth model, while the annual transportation

capacity of rockets C_r is fixed at 6.25×10^5 metric tons.

To minimize the total cost and transportation time, a dynamic allocation model is proposed: in the early phase, rocket transport is prioritized to leverage its mature capacity; as the transport capacity of the Space Elevator grows, its transportation proportion is gradually increased. Specifically, let $\alpha(t)$ denote the transportation proportion of the Space Elevator in year t , then:

$$Q_e(t) = \alpha(t) \cdot \min(C_e(t), D(t)) \quad (13)$$

$$Q_r(t) = (1 - \alpha(t)) \cdot \min(C_r, D(t)) \quad (14)$$

where $D(t)$ represents the remaining untransported volume in year t . If the remaining volume is less than the capacity of the space elevator, only the remaining volume can be transported. $\alpha(t)$ is designed as a time-increasing sigmoid function:

$$\alpha(t) = \frac{1}{1 + e^{-k(t-t_0)}} \quad (15)$$

Dynamic Allocation Function: $\alpha(t) = 1 / (1 + e^{-k(t-t_0)})$

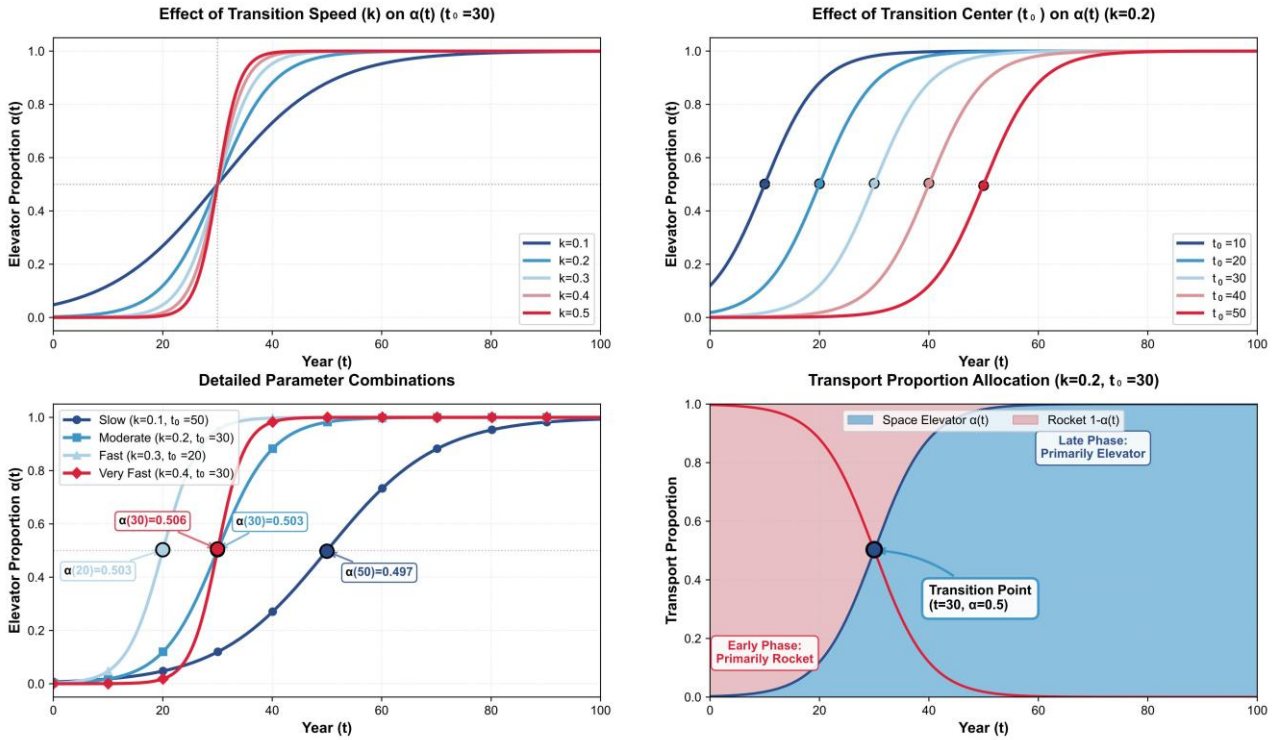


Figure 2: Analysis of the sigmoid function for the dynamic allocation function of the hybrid transportation strategy

The parameter k controls the transition speed, and t_0 is the transfer midpoint. Minimization of the total cost is achieved by optimizing k and t_0 . Based on sensitivity analysis, $k = 0.2$ (moderate transition speed) and $t_0 = 30$ years are set to balance cost and time efficiency. After launch in 2050, the equilibrium point where the elevator and rockets each carry 50% of the transport volume is reached in the 30th year, as shown in Figure 2.

The total transportation cost of the Hybrid Combination Scheme satisfies:

$$C_{total}^H = \sum_{t=0}^T [Q_e(t) \cdot c_e(t) + Q_r(t) \cdot c_r] \quad (16)$$

2.1.4. Transportation Scheme Evaluation (AHP)

To comprehensively evaluate the performance of the Pure Traditional Rocket Network, Pure Space Elevator System, and Hybrid Combination Scheme in terms of transportation

time and cost, and to support the selection of the optimal transport strategy, the Analytic Hierarchy Process (AHP) is adopted to construct an evaluation model. AHP is a multi-criteria decision-making method suitable for systematic evaluation and ranking in scenarios where both qualitative and quantitative factors coexist.

The goal Layer is to select the optimal moon colony material transportation scheme. The criterion layer comprises two core dimensions: C_1 is transportation time (years), reflecting the construction cycle and advancement speed of the project; C_2 is total transportation cost (billion USD), reflecting the economic investment of the project and financial feasibility. The alternative layer includes three alternative options: P_1 (Pure Space Elevator System), P_2 (Pure Traditional Rocket Network), and P_3 (Hybrid Combination Scheme).

In large-scale space infrastructure projects, considering

factors such as technical complexity, resource limitation, and risk management, time nodes typically have stronger constraints and decision-making influence than cost control. Based on this, time is deemed slightly more important than cost. Using the Saaty 1-9 scale method, the importance scale of time relative to cost is set at 3, and the judgment matrix is constructed accordingly.

2.2. Results

Using the constructed dynamic transportation model and

the comprehensive evaluation framework based on AHP, a quantitative analysis was conducted on the core performance indicators (transportation time, total cost) and overall advantages of the three transportation schemes (Pure Space Elevator System, Pure Traditional Rocket Network, and Hybrid Combination Scheme), addressing the transportation requirements of 100 million tons of materials for moon colony construction. The results are shown in Tables 1 and Figure 3.

Table 1: AHP composite scores under different growth rates

Scheme	Score (r=3%)	AHP Composite Score (r=5%)	AHP Composite Score (r=7%)
P1 (PSES, r=5%)	1.52318	1.74745	1.89672
P1 (PSES, No Growth)	1.78643	2.01407	2.15739
P2 (Pure Rocket)		0.887	
P3 (HCS, r=5%)		0.932	
P3 (HCS, No Growth)		0.741	

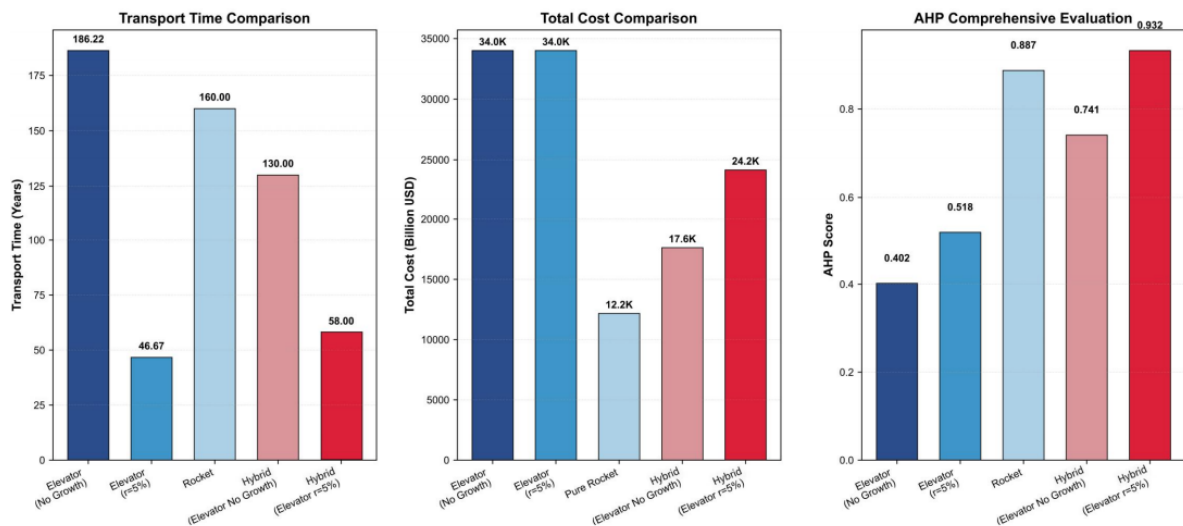


Figure 3: Comparison of material transportation schemes: time, cost, and AHP evaluation

Comparison of material transportation schemes: time, cost, and AHP evaluation are shown in figure 3. The hybrid scheme emerges as the optimal option with the highest AHP score of 0.932. In the early phase, this scheme leverages the mature, low-cost capacity of rockets; in the mid-to-late phase, it gradually integrates space elevators which have growth potential. This configuration significantly reduces total transportation duration while effectively constraining total costs, achieving the optimal trade-off between efficiency and cost.

The pure rocket scheme (0.887) and hybrid (r = 0) scheme (0.741) rank 2nd and 3rd, respectively. The pure rocket scheme exhibits the lowest cost and strong competitiveness, yet its prolonged transportation time impedes project scheduling; while the hybrid (r = 0) scheme outperforms the non-growth elevator scheme in terms of timeliness, it lacks long-term advantages enabled by technological growth.

The pure elevator (r = 5%) scheme (0.518) and pure elevator (0.402) scheme (0.402) yield relatively low scores. The former delivers high efficiency but incurs excessively high total costs; the latter faces the dual drawbacks of long cycle time and high costs, underscoring the critical role of

technological advancement in enhancing the feasibility of space elevators.

3. Conclusions

This study systematically compares three Earth-Moon transport architectures in executing a 100-million-ton cargo transfer mission through a dynamic logistics growth model. Results confirm that the hybrid transport strategy—leveraging mature rocket capacity initially and exploiting space elevator economies of scale later—achieves highest efficiency, with its composite score under baseline technology growth rates significantly surpassing single-mode approaches. The model successfully identifies technology learning rates and allocation midpoints as core sensitivity factors influencing total cost and schedule. However, the current model retains limitations, primarily relying on deterministic steady-state assumptions while neglecting complex impacts of space environment random disturbances—such as orbital debris impacts, cable oscillations, and launch mission failures—on actual system availability. Future research should focus on incorporating stochastic process models to assess system robustness under non-ideal conditions, while

refining quantitative metrics for environmental pollution and carbon footprint. This will establish a more comprehensive and in-depth decision support system for interstellar logistics.

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