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A Physical–Economic Coupling Modeling and Weighted Bi-Objective Optimization Framework for Large-Scale Transportation Systems

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Abstract. This paper constructs a physical-economic coupling model integrating space elevators with traditional rockets for multi-billion-ton Earth-Moon material transport missions. Within a unified framework, it delineates the intrinsic relationships among transport capacity, time cycles, and economic costs. Based on dynamic analysis and energy consumption calculations, a dual-objective planning model targeting total project duration and total cost is established by incorporating unit cost functions and annual transport capacity constraints. A time-cost Pareto frontier is constructed using a weighted summation method. The model achieves multi-year optimized resource allocation through capacity constraints and cumulative demand conditions. It also designs a dynamic allocation mechanism prioritizing full elevator utilization with flexible rocket compensation, enabling synergy between low-cost baseline transport capacity and high-mobility acceleration capabilities. Results demonstrate that this method systematically reveals economies of scale and marginal cost differences across transport architectures, forming a continuously adjustable time-cost tradeoff range. This provides a universally applicable optimization framework and theoretical foundation for comprehensive decision-making in large-scale deep-space engineering.

Keywords: Physical–Economic Coupling Model; Multi-Objective Programming; Multi-Stage Resource Allocation.

1. Introduction

As deep space exploration and extraterrestrial resource development accelerate, large-scale interplanetary material transportation has increasingly become a critical factor constraining the efficiency and economic viability of space engineering projects. How to achieve coordinated optimization among transport capacity, construction cycles, and investment scale under complex dynamic constraints and high engineering costs has emerged as a core challenge requiring urgent resolution in the field of space systems engineering. Traditional research has predominantly focused on single transport modes, emphasizing either payload capacity or energy consumption analysis, while neglecting system-level optimization under multi-modal coordination conditions. Concurrently, existing methodologies often treat time or cost as singular objectives, failing to capture the structural trade-offs between them and lacking a unified algorithmic framework to support integrated decision-making [1]. To address these shortcomings, this paper establishes a dual-objective optimization framework coupling physical and economic factors, integrating dynamic analysis, transport capacity upper bounds, and cost function expressions into a unified modeling system. Building upon this foundation, it introduces a dual-objective planning structure for time and cost, generating a continuous Pareto optimal solution set through weighted scalarization methods to achieve dynamic allocation and structural optimization of multi-year transport resources. This framework emphasizes a “basic capacity-resilient compensation” coordination mechanism. By linking standardized allocation strategies with capacity constraints, it establishes an expandable and generalizable multi-modal transportation optimization paradigm [2, 3].

Using a billion-ton Earth-Moon material transport mission as an application scenario, this paper systematically compares the differences between space elevators and traditional rockets in terms of economies of scale and marginal costs, revealing the continuous trade-off characteristics of hybrid transport structures between compressing project duration and controlling costs. The proposed algorithmic model is not only applicable to Earth-Moon engineering but also provides methodological references for other large-scale complex transport systems [4].

2. Basic Model of Earth-Moon Material Transportation Based on Multi-Objective Programming

2.1. Physical-Economic Coupling Modeling of Dual-Modal Earth-Moon Transportation System

To support the engineering decision-making for the 100-million-ton Earth-Moon material transportation task, it is necessary to characterize the coupling relationship among transportation capacity, time period and economic cost within a unified framework. A dual-modal transportation model composed of a space elevator system and a traditional rocket system is constructed. The physical-economic coupling structure is established through dynamic analysis and cost quantification, providing a parameter basis and constraint boundary for the subsequent multi-objective optimization.

System modeling includes three core aspects: Dynamics and transportation period analysis of the space elevator; Energy consumption and mass ratio calculation of rocket orbital transfer; Expression of cost function and scale constraint.

This coupling model not only characterizes the physical performance of a single transportation mission, but also reflects the decisive influence of the annual throughput upper limit on the overall construction period.

2.1.1. Space Elevator Transportation Time and Dynamic Constraints.

The space elevator connects the Galactic Port on the Earth's equator with the outer vertex anchor of the geosynchronous orbit via high-strength cables, realizing continuous material transportation. The motion of the payload on the cable is jointly affected by the Earth's gravity and centrifugal force, and its net acceleration is:

$$a(r) = -\frac{GM}{r^2} + \omega^2 r \tag{1}$$

Where G is the gravitational constant, M is the mass of the Earth, and ω is the angular velocity of the Earth's rotation.

The net acceleration is zero at $r = r_{GEO} \approx 42{,}164$ km, and centrifugal force dominates in the outer region. To maintain the stable tension of the system, the vertex anchor is set at $r_a = 100{,}000$ km.

Assuming that the climber operates along the cable at a constant speed $v_c = 200$ m/s, the one-way transportation time is $t_{SE} = \frac{r_a - R_E}{v_c}$.

Substituting the parameters yields: $t_{SE} \approx 5.78 \times 10^5$ s ≈ 6.7 days

This period determines the annual round-trip times of a single climber, which is the basis for calculating the annual throughput capacity of the system. Different from the pulsed rocket launch, the elevator system has the characteristic of continuous transportation and presents an obvious advantage of stable capacity in large-scale tasks.

2.1.2. Energy Consumption Model of Traditional Rocket for Earth-Moon Transfer Orbit.

Traditional rockets adopt the Hohmann transfer orbit to complete Earth-Moon transportation. Under the condition of ignoring atmospheric resistance and based on the ideal two-body assumption, the average Earth-Moon distance is: $d_{EM} \approx 384,400$ km.

The velocity increment at the perigee is:

$$\Delta v_1 = \sqrt{\frac{GM_E}{R_E}}\left(\sqrt{\frac{2d_{EM}}{R_E + d_{EM}}} - 1\right) \tag{2}$$

The velocity increment in the lunar braking phase is:

$$\Delta v_2 = \sqrt{\frac{GM_M}{R_M}}\left(\sqrt{\frac{2d_{EM}}{d_{EM} + R_M}} - 1\right) \tag{3}$$

The total velocity increment is approximately: $\Delta v \approx 6.1$ km/s.

According to the Tsiolkovsky formula:

$$\frac{m_0}{m_p} = \exp\left(\frac{\Delta v}{I_{sp} g_0}\right) \tag{4}$$

When $I_{sp} = 360$ s, the ratio of initial mass to payload mass is about 4.3.

This means that rocket transportation has a significant structural and fuel ratio burden, resulting in high energy consumption cost per unit payload.

2.1.3. Cost Structure and Scale Effect Analysis.

(1) Cost Model of the Space Elevator System

The total annual cost of the space elevator system is expressed as:

$$C_{SE} = C_{fix} + N_{climb} \cdot c_{unit} \tag{5}$$

Where: Annualized fixed cost $C_{fix} = 1.2 \times 10^{11}$ USD; Marginal cost per single lift $c_{unit} = 5 \times 10^5$ USD.

The maximum annual capacity of a single Galactic Port is: 1.79×10^5 ton/year. The total annual upper limit of three ports is: $X_{SE,max} = 5.37 \times 10^5$ ton/year.

Under the effect of scale effect, its unit transportation cost can be controlled at $c_{SE} \approx 2 \times 10^5$ USD/ton.

The advantage of the elevator system is reflected in the low marginal cost under long-term stable operation.

(2) Cost Model of the Traditional Rocket System

Assuming 10 launch sites globally with an annual launch limit of 12 times per site, the annual number of system launches is: $F_{rocket,max} = 120$. Taking the single payload as 125 ton, the maximum annual capacity is $Y_{R,max} = 1.5 \times 10^4$ ton/year .

The unit transportation cost can be expressed as:

$$c_R = \alpha + \beta m_{fuel} \tag{6}$$

Calculated based on the comprehensive mass ratio relationship: $c_R \approx 3.44 \times 10^6$ USD/ton .

The rocket transportation cost is more than 17 times that of the elevator system, and the annual throughput capacity is significantly limited.

2.1.4. Capacity Constraints and Feasible Region Expression.

Define decision variables: x_t^{SE} : Transportation mass of the elevator in the t -th year; y_t^R : Transportation mass of the rocket in the t -th year

The constraints are:

$$x_t^{SE} \le 5.37 \times 10^5, \ y_t^R \le 1.5 \times 10^4 \tag{7}$$

It can be seen that the annual throughput capacity of the rocket system is only about 2.8% of that of the elevator system. Under the 100-million-ton construction scale, this difference will directly determine the lower limit of the construction period.

The above constraints form the feasible region boundary of the subsequent multi-stage optimization model.

2.2. Engineering Comparison of Three Transportation Scenarios

Under the condition of total transportation demand $M = 10^8$ ton , boundary calculations are carried out for two extreme transportation scenarios.

Table 1. Three Scheme comparing

Scenario	Completion Time (years)	Unit Cost (USD/ton)	Total Cost (USD)
Space elevator only	187	2×10^5	2.0×10^{13}
Traditional rocket only	6667	3.44×10^6	3.44×10^{14}

Where:

$$T_{SE} = \frac{10^8}{5.37 \times 10^5} \approx 187 \text{ years}, \ T_R = \frac{10^8}{1.5 \times 10^4} \approx 6667 \text{ years} \tag{8}$$

It can be seen that:

The pure rocket scheme is obviously inferior to the elevator scheme in both time and cost dimensions, and has no engineering feasibility;

The pure elevator scheme has the lowest unit cost, but the construction period is limited by the fixed throughput capacity, forming the lower time bound.

Between the above two extreme solutions, a series of time-cost trade-off solutions can be formed by introducing rockets to supplement the annual capacity gap of the elevator. The hybrid transportation strategy will be systematically solved through a dual-objective optimization model.

3. Analysis of Time-Cost Pareto Optimal Solutions Under Three Transportation Scenarios

3.1. Construction of Bi-Objective Optimization Model

To systematically evaluate the trade-off between construction period and economic investment of different transportation architectures, a bi-objective programming model is constructed with the objectives of minimizing total transportation time T and minimizing total transportation cost C. The decision variables are the mass allocation sequences transported by space elevator and traditional rocket in each year: $\{x_t^{SE}, y_t^R\}$.

Under the constraint of total transportation demand $M = 1\times10^8$ ton, the cumulative transportation condition shall be satisfied:

$$\sum_{t=2050}^{T_{end}} \left(x_t^{SE} + y_t^R\right) \geq M \tag{9}$$

Where the task completion time is defined as: $T = T_{end} - 2049$.

The total cost function is expressed as:

$$C = \sum_{t=2050}^{T_{end}} \left(c_{SE} x_t^{SE} + c_R y_t^R\right) \tag{10}$$

The unit transportation costs are taken as: $c_{SE} = 2\times10^5$ USD/ton, $c_R = 3.44\times10^6$ USD/ton.

Meanwhile, the annual capacity constraints are satisfied:

$$x_t^{SE} \leq X_{SE,max}, \quad y_t^R \leq Y_{R,max} \tag{11}$$

This model forms a typical time-cost bi-objective resource allocation structure, in which the elevator system provides low-cost basic transportation capacity, while the rocket system undertakes the high-cost accelerated compensation function.

To construct the time-cost Pareto optimal solution set, the Weighted Sum Method is adopted to scalarize the bi-objective function. The comprehensive objective function is defined as:

$$\min Z = \lambda \frac{T}{T_{ref}} + (1-\lambda)\frac{C}{C_{ref}}, \quad \lambda \in [0,1] \tag{12}$$

Where: λ is the weight coefficient; T_{ref} and C_{ref} are the normalized reference values of time and cost, respectively.

By changing the weight parameter λ, different time-cost trade-off solutions can be obtained. When $\lambda \to 1$, the optimization objective tends to minimize the completion time; when $\lambda \to 0$, the optimization objective tends to minimize the total cost.

Under the annual capacity constraints, solving the scalarized objective function can yield the corresponding transportation allocation sequence $\{x_t^{SE}, y_t^R\}$. With the continuous variation of the weight parameter, a set of non-dominated solutions can be formed, thereby constructing the time-cost Pareto frontier.

The pure elevator and pure rocket scenarios correspond to the two extreme boundary solutions of the weight values respectively.

3.2. Pure Space Elevator Scenario

In the scenario where only three Galactic Ports are used for material transportation, the annual transportation volume is limited by: $X_{SE,max} = 5.37 \times 10^5$ ton/year.

The minimum completion time is:

$$T_a = \frac{1 \times 10^8}{5.37 \times 10^5} \approx 187 \text{ years} \tag{13}$$

The corresponding total cost is:

$$C_a = 1 \times 10^8 \times 2 \times 10^5 = 2 \times 10^{13} \text{ USD} \tag{14}$$

Since the system capacity is constant with no other compensation mechanism, the only feasible solution in this scenario is located at: $(T, C) = (187, 2 \times 10^{13})$.

This point constitutes the low-cost endpoint of the time-cost Pareto frontier.

As shown in Fig. 1, the total system capacity is dominated by the space elevator, and the annual throughput of the Galactic Port is orders of magnitude higher than that of traditional rocket launch sites. The annual capacity of the rocket system is only about 2.8% of that of the elevator system.

This order-of-magnitude difference provides an engineering basis for the setting of $X_{SE,max} \gg Y_{R,max}$ in the model, highlighting the scale advantage of the space elevator in handling large-scale material transfer tasks.

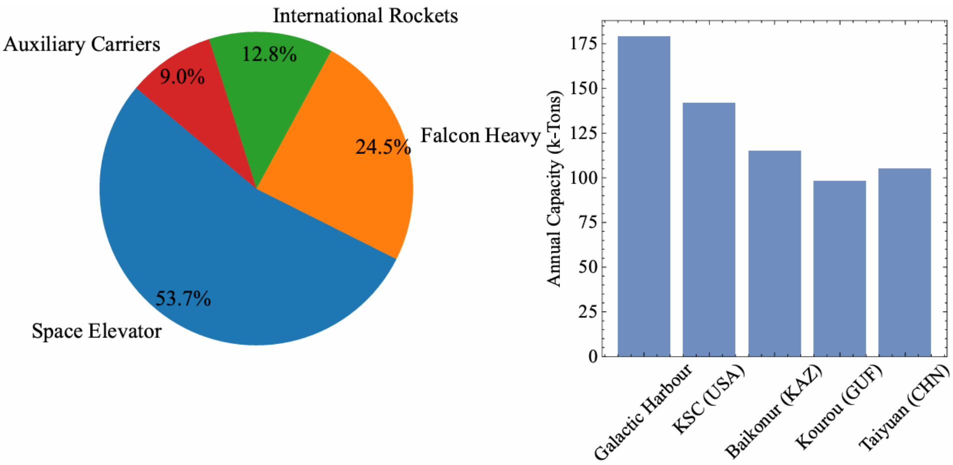

Figure 1. Comparison of capacity composition of space elevator and rocket transportation systems and annual throughput of each launch site

3.3. Pure Rocket Transportation Scenario

In the scenario completely relying on the rocket system, the annual transportation capacity is:

$$Y_{R,max} = F_{rocket,max} \cdot m_{payload} = 120 \times 125 = 1.5 \times 10^4 \text{ ton/year} \quad (15)$$

The time required to complete the entire construction task is:

$$T_b = \frac{1 \times 10^8}{1.5 \times 10^4} \approx 6667 \text{ years} \quad (16)$$

The corresponding total cost is:

$$C_b = 1 \times 10^8 \times 3.44 \times 10^6 = 3.44 \times 10^{14} \text{ USD} \quad (17)$$

Due to the severely limited capacity, this scenario is dominated by the pure elevator scheme in both time and cost dimensions and has no engineering feasibility.

3.4. Hybrid Transportation Mode and Dynamic Flow Allocation Mechanism

To explore the continuous trade-off between time and cost, a joint scheduling structure is introduced. The annual allocation ratio is defined as: $\alpha_t \in [0,1]$ [5].

It can be formally written as:

$$x_t^{SE} = \alpha_t X_{SE,max}, \quad y_t^R = (1-\alpha_t) Y_{R,max} \quad (18)$$

Considering that the unit cost of the elevator system is significantly lower than that of the rocket system, a heuristic allocation rule of prioritizing full-load operation of the elevator is adopted [6]:

$$x_t^{SE} = \min(X_{SE,max}, M_t), \quad y_t^R = \max(0, M_t - X_{SE,max}) \quad (19)$$

Where M_t is the remaining demand in the t-th year.

When the target construction period $T_c < 187$ years, the required average annual transportation volume is: $\frac{M}{T_c}$. If this value exceeds the annual upper limit of the elevator, rockets must be introduced to undertake the differential transportation. As the target time is gradually compressed, the proportion undertaken by rockets increases monotonically, and the total cost rises accordingly, thus forming a continuous non-dominated solution set in the time-cost plane.

As shown in the left diagram of Fig. 2, the initial delivery progress comparison verifies the effectiveness of the annual capacity constraints. The hybrid mode shows a higher growth slope at the initial stage of the task, and the rocket compensates for the elevator capacity gap to realize rapid material deployment.

The right diagram of Fig. 2 shows that under the dynamic allocation strategy, the elevator system always maintains full-load operation, while the rocket system undertakes elastic compensation, so as to ensure the accelerated growth of cumulative delivery volume. This indicates that multi-modal collaboration can significantly shorten the construction period.

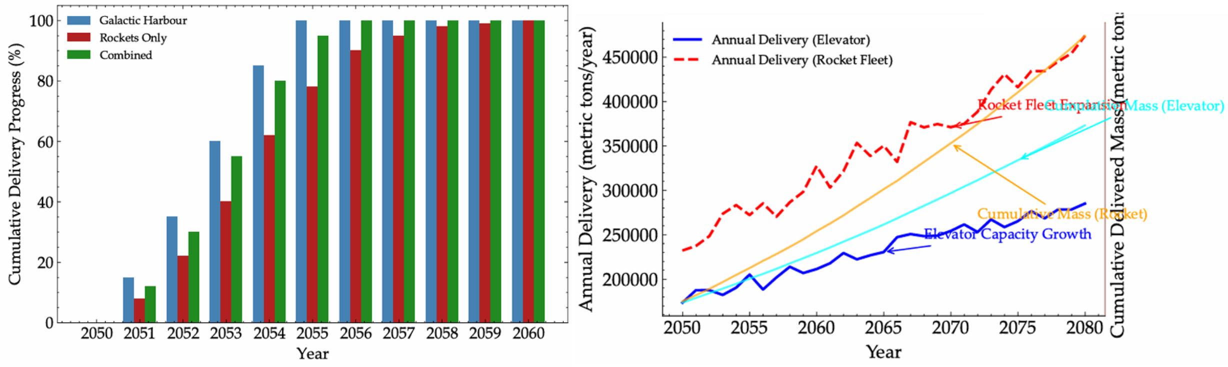

Figure 2. Time-series comparative analysis of delivery progress and volume allocation of space transportation schemes

3.5. Time-Cost Trade-Off Characteristics

As shown in the left diagram of Fig. 3, there are significant differences in the variation trend of cumulative delivery volume with time under different transportation scenarios. The hybrid transportation system achieves a higher phased growth slope by superposing the basic capacity of the elevator and the supplementary capacity of the rocket.

The right diagram of Fig. 3 further reveals the dynamic coupling relationship between cumulative transportation volume and cost expenditure. The elevator system contributes the main transportation volume and maintains low-cost growth, while the rocket system significantly increases the total expenditure but provides necessary acceleration capacity at key time nodes.

The above results show that the hybrid strategy can form a continuous trade-off interval between time compression and cost increase, constituting a Pareto efficient solution set in the sense of bi-objective optimization.

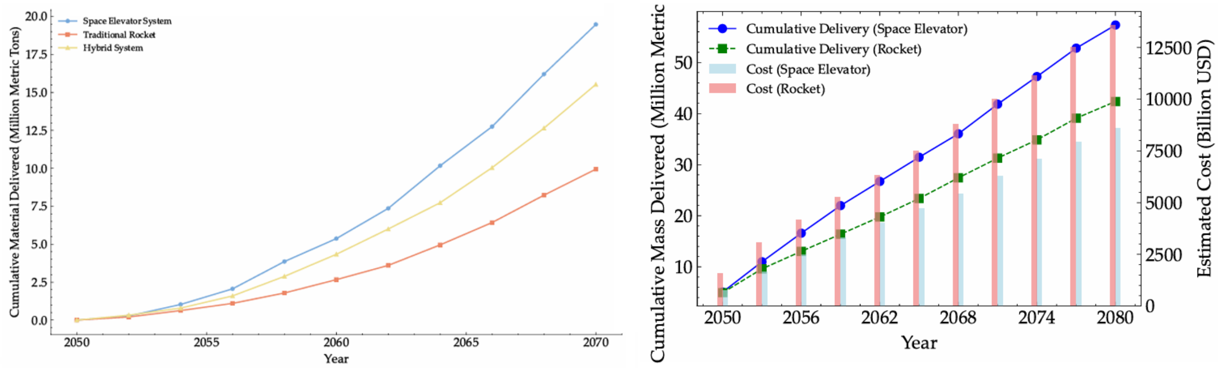

Figure 3. Comprehensive analysis chart of material delivery trend and cost-benefit under different transportation schemes

4. Conclusion

This paper proposes a physical-economic coupled dual-objective optimization model for ultra-large-scale Earth-Moon material transportation missions, providing a structured algorithmic framework for time-cost synergistic decision-making in complex engineering systems. First, by uniformly embedding dynamic constraints, energy consumption relationships, and unit cost functions within annual transport capacity boundaries, the model quantitatively characterizes the engineering feasibility domain, enabling comparability and computability of different transport modes within the same framework. Second, leveraging dual-objective programming and a continuous weight parameter adjustment mechanism, a time-cost tradeoff path is constructed. Using unit cost differences as a quantitative basis, the model reveals the profound impact of economies of scale on resource allocation structures. Subsequently, by introducing a “base full-load-flexible compensation” dynamic allocation rule, high-capacity systems and high-mobility systems achieve synergistic complementarity, effectively compressing construction cycles while satisfying total demand constraints. Finally, the model combines engineering interpretability with decision-support functionality, providing theoretical reference for major spatial infrastructure planning and related science-technology-economic strategies. Future research may further explore uncertainty scenarios and multi-stage investment structure analysis.

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