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Cislunar Transportation Optimization Framework Based on Weighted Multi-Objective Optimization and Negative Binomial Reliability Modeling

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Abstract: This paper develops a decision-making framework for large-scale Earth–Moon material transportation that balances transportation efficiency and economic cost. We first construct transportation models for both the space elevator system and conventional rocket launches, characterizing their operational behavior through capacity constraints and cost functions. Based on these models, we develop a hybrid transportation optimization model that allocates cargo mass between different transportation routes. We then formulate a weighted multi-objective optimization model to jointly optimize transportation time and total cost. To account for uncertainty in rocket launches, we introduce a reliability analysis framework based on the negative binomial distribution, which captures the influence of launch success probability on transportation duration and cost. Numerical results show that the proposed framework achieves a stable trade-off between efficiency and cost while maintaining robust performance under varying launch reliability conditions. The framework provides a practical modeling approach for planning large-scale space transportation systems.

Keywords: Multi-Objective Optimization; Negative Binomial Reliability Model; Hybrid Transportation Optimization Model.

1. Introduction

As deep space exploration progresses and plans for lunar base construction accelerate, the efficient transportation of large quantities of materials between Earth and the Moon has become a critical challenge in aerospace engineering. Future lunar infrastructure development will require the continuous delivery of large amounts of equipment and construction materials. Consequently, balancing transportation capacity, economic cost, and delivery time has become a key issue in planning complex space transportation systems.

At present, most large-scale space transportation relies on rocket launches. However, in high-frequency transportation scenarios, rocket-based delivery faces challenges such as high launch costs and long transportation cycles. Meanwhile, emerging technologies such as space elevators have attracted increasing attention due to their potential for large-scale and low-cost transportation. Despite this potential, systematic modeling of space elevator capacity and its coordination with conventional rocket transportation systems remains limited.

Existing studies mainly evaluate the capacity or cost of individual transportation modes, while relatively few provide a unified modeling framework for multi-path collaborative transportation systems. In addition, rocket launches involve inherent failure risks, and such uncertainties can significantly influence transportation efficiency and cost. These factors are often difficult to capture using traditional deterministic models [1][2].

To address these issues, this paper develops a unified modeling framework for Earth–Moon transportation systems. We first construct transportation models for both the space elevator and rocket systems, using capacity constraints and cost functions to characterize their operational features. Based on these models, we develop a hybrid transportation allocation model that distributes cargo mass between the two routes. We then apply a weighted multi-objective optimization approach to jointly optimize transportation time and cost. Finally, we introduce a reliability analysis model based on the negative binomial distribution to capture the influence of launch success probability on system performance [3][4]. The proposed framework provides a quantitative basis for planning complex space transportation systems, consistent with recent developments in lunar exploration programs such as Artemis [5]

2. Transportation System Modeling

This section develops mathematical models to evaluate alternative transportation strategies for delivering construction materials to the Moon. Three scenarios are considered: a Space Elevator-only strategy, a Rocket-only strategy, and hybrid strategies combining both systems. The models estimate system capacity, completion time, and total cost.

2.1. Space Elevator Transportation Model

Goal: This subsection evaluates the transportation capacity, completion time, and cost when the space elevator system is adopted as the primary transportation mode.

Step 1: Describe the two-stage transportation route.

The Space Elevator route consists of two sequential stages:

Earth port → elevator apex via the Space Elevator;

Apex → Moon colony via rocket transfer.

Since cargo must pass through both stages, the overall system throughput is determined by the bottleneck capacity.

Step 2: Compute the stage-1 capacity.

Assume the system contains H Galactic Harbours, each capable of transporting q tons per year. Let a denote the operational availability factor accounting for maintenance or downtime. The annual lifting capacity is therefore $C_E = aHq$.

Step 3: Define the stage-2 capacity.

Let C_{EM} denote the annual transfer capacity from the elevator apex to the lunar colony: $C_{EM} = \text{given/assumed (tons/year)}$.

Step 4: Determine the effective system capacity.

Because both stages are required for each delivered ton, the effective annual throughput is determined by the bottleneck stage:

$$C_E^{eff} = \min(C_E, C_{EM}) \tag{1}$$

Step 5: Estimate the completion time.

To deliver a total mass M, the operating duration is determined by the effective capacity:

$$Y_E = \left\lceil \frac{M}{C_E^{eff}} \right\rceil \tag{2}$$

Step 6: Formulate the total cost.

The total cost includes three components: capital expenditure F, annual operational cost O, variable transportation costs.

Let v_E denote the cost of lifting cargo from Earth to the apex, and v_{EM} denote the cost of transferring cargo from the apex to the Moon. The total cost becomes

$$M_e = F + OY_E + (v_E + v_{EM})M \tag{3}$$

The elevator strategy becomes economically favorable when the combined unit transportation cost $(v_E + v_{EM})$ is significantly lower than the cost of direct rocket transport.

2.2. Rocket Transportation Model

Goal: This model estimates the transportation time and cost when all cargo is delivered using conventional rocket launches. We convert launch frequency into annual transportation capacity and accumulate it over time.

Step 1: Define launch frequency data.

Let $N_{s,t}$ denote the number of launches from site s in year t.

Step 2: Compute the average launch frequency.

We compute the average launch frequency for each site over the observation window T:

$$N_s = \frac{1}{|\mathrm{T}|} \sum_{t \in \mathrm{T}} N_{s,t} \tag{4}$$

Step 3: Aggregate all launch sites.

Summing the average launch frequencies across all launch sites yields the total expected number of launches per year.

Step 4: Convert launch frequency into annual transport capacity.

If each rocket carries m tons of payload, the annual rocket transportation capacity is $C_A = mn$, where n denotes the total annual number of launches.

Step 5: Estimate the completion time.

Under constant capacity, the cumulative delivered mass after Y years is $C_T(Y) = YC_A$.

To satisfy the required transportation mass M, the project duration becomes

$$Y = \left\lceil \frac{M}{C_A} \right\rceil = \left\lceil \frac{M}{mn} \right\rceil \tag{5}$$

If the total annual launch frequency is known directly (e.g., $n = 1200$), the intermediate aggregation step can be omitted.

Step 6: Formulate the rocket transportation cost.

We assume that rocket transportation cost is proportional to the number of launches. Let f_s denote the cost per launch at site s, and N_s denote the average launch frequency at that site. Let S denote the set of rocket launch sites. The annual rocket expenditure is therefore

$$C_R = \sum_{s \in S} f_s N_s \tag{6}$$

Assuming launch frequencies remain stable, the total cost over Y years is $M_r(Y) = YC_R$.

The rocket transportation strategy is straightforward and operationally flexible, but its total cost and completion time strongly depend on launch frequency and payload capacity. When launch rates are limited, the overall delivery process becomes very time-consuming.

2.3. Hybrid Cost Optimization Model

Goal: This subsection aims to determine the cost-optimal allocation of transportation tasks between the space elevator route and the direct rocket route.

Step 1: Define the mass allocation ratio.

Let $c \in [0,1]$ denote the fraction of mass transported via the elevator route. The mass allocation is $M_E = cM$, $M_R = (1-c)M$, where M_E and M_R denote the masses assigned to the elevator route and rocket route, respectively.

Step 2: Determine the effective elevator capacity.

Because the elevator route requires two stages, its effective annual capacity is

$$C_E^{eff} = \min(C_E, C_{EM}) \tag{7}$$

Step 3: Impose the elevator capacity constraint.

The transported mass via the elevator must satisfy

$$M_E \le YC_E^{eff} \Leftrightarrow cM \le Y \min(C_E, C_{EM}) \tag{8}$$

Step 4: Impose the rocket capacity constraint.

If rockets have annual capacity C_A, then

$$M_R \le YC_A \Leftrightarrow (1-c)M \le YC_A \tag{9}$$

Step 5: Formulate the hybrid total cost.

The total cost under hybrid operation becomes

$$C(c,Y) = F + OY + (v_E + v_{EM})cM + v_R(1-c)M \tag{10}$$

where v_R denotes the unit transportation cost of rocket delivery.

Step 6: Define the optimization objective.

The optimal allocation minimizes total transportation cost:

$$\min_{0\le c\le 1, Y\in \mathbb{Z}^{+}} C(c,Y) \tag{11}$$

The optimal value of c balances the lower unit cost of elevator transport against the higher throughput of rocket launches.

The hybrid strategy allows the system to combine the low unit cost of the elevator route with the flexibility of direct rocket transportation. The cost-optimal solution depends on whether the economic advantage of the elevator route outweighs the higher transport speed of rockets.

2.4. Hybrid Time Optimization Model

Goal: This subsection aims to determine the allocation ratio that minimizes the total project completion time when the elevator route and rocket route operate simultaneously.

Step 1: Keep the same mass allocation structure.

Let $c\in[0,1]$ denote the fraction of total cargo transported by the elevator route. Then

$$M_E = cM,\quad M_R=(1-c)M \tag{12}$$

Step 2: Compute the elevator-route transportation time.

The required time for the elevator route is

$$Y_E(c)=\left\lceil \frac{M_E}{C_E^{eff}}\right\rceil=\left\lceil \frac{cM}{\min(C_E,C_{EM})}\right\rceil \tag{13}$$

Step 3: Compute the rocket-route transportation time.

Let C_A denote the annual rocket capacity. The required time for rocket delivery is

$$Y_R(c)=\left\lceil \frac{M_R}{C_A}\right\rceil=\left\lceil \frac{(1-c)M}{C_A}\right\rceil \tag{14}$$

Step 4: Determine the total completion time under parallel operation.

Since both routes operate in parallel, the project completion time is determined by the slower route:

$$Y(c)=\max(Y_E(c),Y_R(c)) \tag{15}$$

Step 5: Define the time-minimization problem.

The minimum completion time is obtained by

$$\min_{0\le c\le 1} Y(c)=\min_{0\le c\le 1}\max\left(\frac{cM}{\min(C_E,C_{EM})},\frac{(1-c)M}{C_A}\right) \tag{16}$$

The time-optimal solution is typically achieved when the two transportation routes finish their assigned tasks at approximately the same time. In this case, the system avoids idle capacity on either route and minimizes the total turnaround time.

2.5. Weighted Multi-Objective Optimization

Goal: This subsection aims to obtain a transportation strategy that balances total cost and project completion time [6].

Step 1: Define the two objectives.

Let $C(c,Y)$ denote the total transportation cost and $Y(c)$ denote the completion time under a given allocation ratio c.

Step 2: Normalize the objectives.

To combine these quantities, we introduce reference values C_{ref} and Y_{ref}:

$$\hat{C}(c)=\frac{C(c,Y(c))}{C_{ref}},\quad \hat{Y}(c)=\frac{Y(c)}{Y_{ref}} \tag{17}$$

Step 3: Construct the weighted objective function.

The weighted objective function is

$$J_\omega(c)=\omega\hat{C}(c)+(1-\omega)\hat{Y}(c) \tag{18}$$

where $\omega\in[0,1]$ controls the trade-off between economic cost and project duration.

Step 4: Solve the optimization problem.

The optimization problem becomes $\min_{0\le c\le 1} J_\omega(c)$.

Step 5: Generate trade-off solutions.

By varying ω over the interval [0,1], we obtain a set of solutions approximating the cost–time Pareto frontier. Numerical results are reported in the results section, as shown in Figure 1.

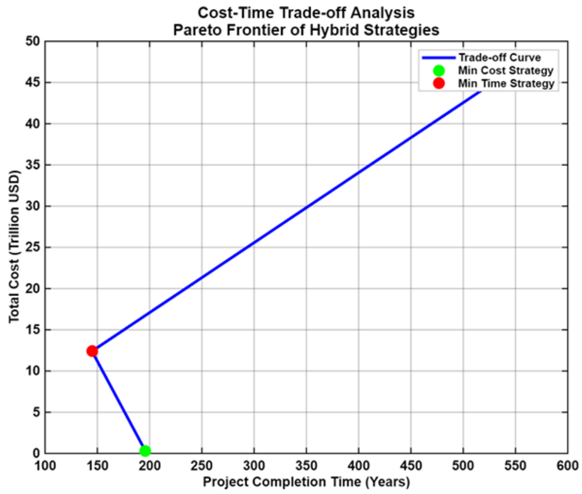

Figure 1. Transport Progress Simulation: Comparison of cumulative delivered mass versus project timeline across the three transportation strategies

This weighted multi-objective framework makes it possible to analyze the trade-off between economic efficiency and transportation speed. Different values of ω reflect different decision preferences and lead to different allocation strategies.

3. Numerical Results

3.1. Parameter Settings and Baseline Assumptions

This section evaluates the transportation strategies using parameter estimates projected for the year 2050. The target mass is $M = 1.0 \times 10^8$ metric tons.

To ensure transparency and reproducibility of the modeling assumptions, the key parameter values used in the transportation model and their corresponding data sources are summarized in Table 1.

Table 1. Key parameters and data sources used in the transportation model

Parameter	Value Used in Model	Reference
Falcon 9 launch cost	$62 million per launch	[7]
Payload capacity to LEO	22,800 kg	[8]
Cost per kg to LEO	$2,700/kg (approx.)	[7]
Launch success probability	0.98 – 0.99 (assumed)	[8]
Space transportation cost modeling basis	Engineering cost framework	[9]
Optimization framework	Multi-objective optimization method	[10]
Reliability model	Negative binomial distribution	[11]

Space elevator system (ideal conditions): Each Galactic Harbour transports $q = 179000$ metric tons/year, and the system contains $H = 3$ harbours. Under ideal conditions, the availability factor is set to $a = 1$. The annual elevator capacity is $C_E = aHq = 537000$ tons/year.

Rocket transportation (ideal conditions): The payload capacity in 2050 is assumed to be $m = 150$ tons/launch. Let n denote the total annual launches across all launch sites. Using $n = 1200$ launches/year, the annual rocket transport capacity is $C_R = mn = 180000$ tons/year.

Rocket launch price and per-ton transport cost: A published heavy-lift commercial launch price $L_R = 97 \times 10^6$ USD/launch is used, the corresponding per-ton transport cost is $v_R = \frac{L_R}{m} \approx 6.467 \times 10^5$.

The apex-to-Moon transfer cost is modeled as a fraction κ of direct rocket cost:

$$v_{EM} = \kappa v_R, \quad \kappa = 0.2 \Rightarrow v_{EM} \approx 1.293 \times 10^5 USD/ton \quad (19)$$

To avoid transfer bottlenecks, the transfer capacity is assumed to satisfy

$$C_{EM} \geq C_E \Rightarrow C_E^{eff} = \min(C_E, C_{EM}) = C_E \quad (20)$$

Space elevator cost structure: $F = 18.6 \times 10^9$ USD, $O = 0.3 \times 10^9$ USD/year, $v_E = 1.0 \times 10^4$ USD/ton.

3.2. Rocket-Only Transportation Results

The completion time under rocket-only transportation is

$$Y_B = \left\lceil \frac{M}{C_R} \right\rceil = \left\lceil \frac{10^8}{180000} \right\rceil = 556\ years \quad (21)$$

The number of launches required is $K = M / m$, hence total cost is

$$Cost_B = \frac{M}{m} L_R = \frac{10^8}{150} \cdot 97 \times 10^6 \approx 6.467 \times 10^{13} USD\ trillion\ USD. \quad (22)$$

3.3. Space Elevator-Only Transportation Results

The completion time under elevator-only transportation is

$$Y_A = \left\lceil \frac{M}{C_E^{eff}} \right\rceil = \left\lceil \frac{10^8}{537000} \right\rceil = 187\ years \quad (23)$$

The total cost includes capital expenditure, operational expenditure, and variable costs:

$$Cost_A = F + OY_A + (v_E + v_{EM})M \approx 1.401 \times 10^{13} USD \quad (24)$$

3.4. Hybrid Transportation Results

Let $c \in [0,1]$ denote the fraction of mass delivered through the elevator route $M_E = cM$, $M_R = (1-c)M$.

(1) Cost-Optimal Allocation:

Since $v_R \gg (v_E + v_{EM})$ under the baseline parameters, the minimum-cost solution assigns all mass to the elevator route: $c_{cost}^* = 1$. Thus, $Y_{cost}^* = 187$ years, $Cost_{cost}^* \approx 1.401 \times 10^{13}$ USD.

(2) Time-Optimal Allocation (Parallel Operation)

Assuming the elevator and rocket systems operate in parallel, the completion time is

$$Y(c) = \max\left(\frac{cM}{C_E^{eff}}, \frac{(1-c)M}{C_R} \right) \quad (25)$$

The balanced (equal-finish) condition yields

$$c_{time}^* = \frac{C_E^{eff}}{C_E^{eff} + C_R} = \frac{537000}{537000 + 180000} \approx 0.749 \quad (26)$$

The minimized completion time becomes

$$Y_{time}^* = \left\lceil \frac{M}{C_E^{eff} + C_R} \right\rceil = \left\lceil \frac{10^8}{717000} \right\rceil = 140 \quad (27)$$

The corresponding cost is in (28)

(3) Compromise Allocation via Knee-Point Selection

Cost minimization drives $c \to 1$, whereas time minimization yields a smaller c. To obtain an objective compromise, a knee-point selection method is applied in the (cost, time) space.

$$Cost^{*}_{time} = F + OY^{*}_{time} + (v_E + v_{EM})c^{*}_{time}M + v_R(1-c^{*}_{time})M \approx 2.673\times10^{13}USD \quad (28)$$

Under parallel operation, completion time and total cost are expressed as

$$Y(c) = \max\left(\frac{cM}{C_E^{eff}}, \frac{(1-c)M}{C_R}\right) \quad (29)$$

$$C(c) = F + OY(c) + (v_E + v_{EM})cM + v_R(1-c)M \quad (30)$$

Candidate solutions are evaluated on a finite grid $C = 0, \Delta c, 2\Delta c, \ldots, 1$ and normalized using

$$\hat{Y}(c) = \frac{Y(c)-Y_{min}}{Y_{max}-Y_{min}}, \quad \hat{C}(c) = \frac{C(c)-C_{min}}{C_{max}-C_{min}} \quad (31)$$

The utopia point is $(0,0)$, and the distance score is

$$D(c) = \sqrt{\hat{Y}(c)^2 + \hat{C}(c)^2} \quad (32)$$

The compromise solution is obtained by

$$c^{*} = \arg\min_{c\in C} D(c) \quad (33)$$

Using the baseline parameters, the algorithm yields $c^{*} \approx 0.95586$ with $Y(c^{*}) = 178$ years, $C(c^{*}) \approx 1.624\times10^{13}$ USD ≈ 16.24 trillion USD.

This allocation assigns approximately 95.6% of the mass to the elevator route while reserving a small rocket fraction to improve completion time, achieving a balanced trade-off between cost and schedule.

4. Reliability Sensitivity Analysis: Rocket Failures

The transportation models developed assume ideal operating conditions. In practice, rocket launches may fail due to mechanical faults, environmental conditions, or operational disruptions. This section introduces a reliability framework to evaluate how launch failures affect transportation time and cost for the rocket-only, elevator-only, and hybrid strategies [12].

Let $p_R \in (0,1]$ denote the probability that a rocket launch succeeds. The corresponding failure probability is $1-p_R$. A successful launch delivers payload, while a failed launch delivers no payload but still consumes resources and incurs cost.

4.1. Stochastic Reliability Model

Assume each successful rocket launch delivers m metric tons of cargo. If a transportation strategy requires M_R tons to be delivered via rockets, the number of successful launches required is $K_R = \left\lceil \frac{M_R}{m} \right\rceil$. Let N_R denote the total number of launch attempts required to obtain K_R successful launches.

Because each rocket launch can be modeled as an independent Bernoulli trial with success probability p_R, the total number of attempts required to achieve K_R successful launches follows a negative binomial distribution. The number of attempts follows a negative binomial distribution: $N_R \sim NegBin(K_R, p_R)$.

$$\mathrm{E}[N_R] = \frac{K_R}{p_R}, \quad Var[N_R] = \frac{K_R(1-p_R)}{p_R^2} \quad (34)$$

For sufficiently large K_R, the distribution can be approximated by a normal distribution.

Let n denote the planned number of rocket launch attempts per year. The rocket transportation time is therefore $Y_R = \frac{N_R}{n}$.

The expected completion time and standard deviation can be approximated by

$$\mathrm{E}[Y_R] \approx \frac{K_R}{np_R}, \quad SD(Y_R) \approx \frac{1}{n}\sqrt{\frac{K_R(1-p_R)}{p_R^2}} \quad (35)$$

These expressions quantify how launch failures inflate project duration and introduce variability in the transportation timeline.

4.2. Impact on Elevator Transportation

The elevator-only strategy developed assumes two stages with bottleneck capacity $C_E^{eff} = \min(C_E, C_{EM})$.

Rocket failures primarily affect the apex-to-Moon transfer stage. Therefore, the effective transfer capacity becomes $C_{EM}^{eff} = p_R C_{EM}$ and the route capacity becomes

$$C_{route}^{eff} = \min(C_E, C_{EM}^{eff}) = \min(C_E, p_R C_{EM}) \quad (36)$$

The elevator-only completion time becomes

$$Y_{elev} = \left\lceil \frac{M}{C_{route}^{eff}} \right\rceil = \left\lceil \frac{M}{\min(C_E, p_R C_{EM})} \right\rceil \quad (37)$$

Launch failures also increase the effective transportation cost of the second stage. If the baseline cost is v_{EM}, the effective cost per ton becomes $v_{EM}^{eff} = \frac{v_{EM}}{p_R}$.

The elevator transportation cost is

$$\mathrm{E}[M_e] \approx F + OY_{elev} + \left(v_E + \frac{v_{EM}}{p_R}\right)M \quad (38)$$

4.3. Impact on Rocket Transportation

For the rocket-only strategy, the entire transportation mass is delivered via rockets $M_R = M$. The number of required successful launches is $K_R = \lceil M / m \rceil$.

The project duration becomes stochastic:

$$Y_{rocket} = \frac{N_R}{n}, \quad N_R \sim NegBin\left(\frac{M}{m}, p_R\right) \tag{39}$$

Compared with the ideal completion time $Y_{rocket}^{(0)} = \left\lceil \frac{M}{mn} \right\rceil$, the expected duration increases approximately by a factor of $1/p_R$. If P_R denotes the cost per rocket launch attempt, the expected transportation cost becomes

$$\mathrm{E}[M_r] = \mathrm{E}[P_R N_R] = P_R \frac{\lceil M / m \rceil}{p_R} \tag{40}$$

4.4. Impact on Hybrid Transportation

For hybrid strategies, the mass allocation remains $M_E = cM, \quad M_R = (1-c)M, \quad 0 \le c \le 1$.

Time Model: The elevator route completion time becomes

$$Y_E(c) = \left\lceil \frac{cM}{\min(C_E, p_R C_{EM})} \right\rceil \tag{41}$$

The rocket route completion time remains stochastic: $K_R(c) = \frac{(1-c)M}{m}$, $N_R(c) \sim NegBin(K_R(c), p_R)$, $Y_R(c) = \left\lceil \frac{N_R(c)}{n} \right\rceil$ with expectation $\mathrm{E}[Y_R(c)] \approx \frac{K_R(c)}{np_R}$.

Under parallel operation, the expected project completion time can be approximated as

$$\mathrm{E}[Y(c)] \approx \max\left(Y_E(c), \mathrm{E}[Y_R(c)]\right) \tag{42}$$

Cost Model: Using the effective transportation costs $v_R^{eff} = \frac{v_R}{p_R}$, $v_{EM}^{eff} = \frac{v_{EM}}{p_R}$, the hybrid cost function becomes

$$\mathrm{E}[C(c,Y)] \approx F + OY + \left(v_E + \frac{v_{EM}}{p_R}\right)cM + \frac{v_R}{p_R}(1-c)M \tag{43}$$

In the weighted multi-objective framework, the deterministic cost and time terms are replaced by their expected values $\mathrm{E}[C(c,Y)]$ and $\mathrm{E}[Y(c)]$.

4.5. Reliability Sensitivity Results

Figure 2 illustrates the sensitivity of the transportation system to rocket launch reliability $p_R \in [0.8, 1.0]$. The results indicate that the impact on both completion time and total cost is approximately linear rather than exponential. When launch reliability decreases from 100% to 80%, the system performance changes as follows:

$$p_R: 100\% \to 80\% \begin{cases} \text{Time: } 145 \to 180 \text{ years} \\ \text{Cost: } 11.8T \to 15.2T \end{cases} \tag{44}$$

This moderate degradation indicates that the transportation framework maintains stable performance even under reduced launch reliability.

Robustness of the Hybrid Strategy: The optimal allocation obtained satisfies $c^* \approx 0.96$. As a result, the sensitivity of the total expected cost to launch reliability becomes negligible.

This allocation effectively isolates the system from launch reliability fluctuations. The hybrid strategy therefore mitigates reliability risk by assigning the majority of the transport workload to the space elevator while using rockets only for marginal acceleration of the delivery schedule.

The reliability analysis demonstrates that the hybrid transportation architecture provides inherent robustness against launch failures. Because only a small portion of the cargo depends on rockets, fluctuations in launch reliability have limited influence on total project cost and schedule. Consequently, the system remains economically viable even when launch reliability decreases substantially.

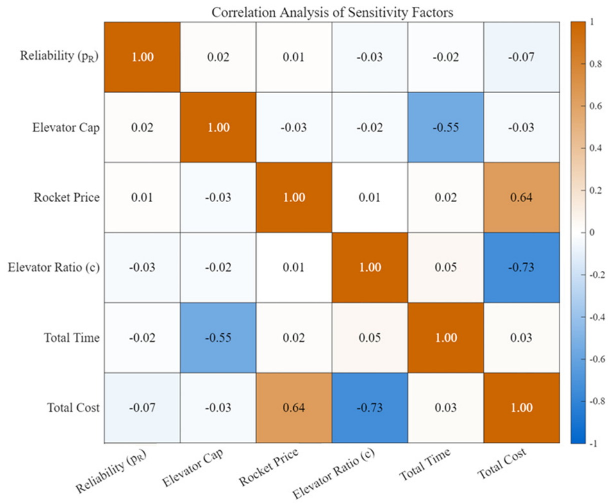

Figure 2. Correlation analysis of key system parameters

Figure 2 presents the correlation relationships between key system parameters and transportation performance indicators. The results indicate that elevator capacity has a strong negative correlation with total project completion time, while rocket transportation cost shows a positive correlation with total system cost. In addition, increasing the elevator allocation ratio significantly reduces the overall transportation cost.

5. Conclusion

This paper investigates the trade-off between efficiency and cost in large-scale Earth–Moon material transportation systems by developing an integrated analytical framework that includes space elevator transportation models, rocket transportation models, and hybrid transportation optimization models. We conduct quantitative comparisons of different transportation strategies under representative system parameters. The results show that transporting 1.0×10^8 tons of cargo using rockets alone would require approximately 556 years, whereas relying solely on a space elevator system would reduce the completion time to about 187 years.

When the two transportation systems operate in parallel with an appropriate allocation of transport tasks, the project completion time can be further reduced to approximately 140 years while keeping the overall cost at a manageable level. Reliability analysis further indicates that when the rocket launch success probability decreases from 100% to 80%, the resulting changes in transportation time and total cost remain relatively moderate. This result demonstrates that the hybrid transportation architecture maintains stable system performance under uncertain launch conditions.

Overall, the proposed modeling and optimization framework provides a quantitative basis for planning complex space transportation systems. Future research may incorporate more detailed engineering parameters and dynamic demand models to further investigate long-term operational strategies for large-scale space transportation systems.

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