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Research on Transportation System Planning for Lunar Colonization Based on Pareto Optimization and Monte Carlo Simulation

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Abstract: Amid Earth's worsening ecological pressure and resource conflicts, the Moon is humanity's top choice for the first extraterrestrial colony. The 2050-launched 100,000-person lunar colony requires transporting 100 million tons of construction materials and securing long-term stable water supply. This paper builds a multi-model collaborative framework to evaluate lunar transportation schemes from cost, time, reliability and environmental impact perspectives. A weighted bi-objective optimization model for minimizing cost and time is constructed, and Pareto frontier analysis yields an optimal hybrid transportation ratio with a total cost of $\$1.08\times10^{12}$ and a 148.98-year duration. Monte Carlo simulation quantifies four failure scenarios' impacts: rocket failures barely affect transportation time, while elevator and extreme failures cause severe delays and performance decline, requiring a 30-year buffer and a $221.4 billion contingency budget. Additionally, a regression forecasting-MOEA/D integrated framework estimates the colony's annual water demand at 270,000 tons, verifying that elevator-dominated transportation is more economically efficient and operationally reliable for long-term lunar water supply.

Keywords: Moon Colony, Pareto Optimization, MOEA/D.

1. Introduction

With the continuous development of human society and science and technology, the ecological pressure on the Earth has intensified, and the contradiction between population and resources is becoming increasingly acute. Exploring outer space and building space habitats has become a key path to alleviate ecological pressure and expand the boundaries of human survival. As the closest celestial body to the Earth, the Moon, with its unique location and environmental conditions, has become the top choice for humanity's first extraterrestrial colony.

To realize this vision, the electric-powered space elevator system and iteratively advanced traditional rocket technology are the two primary options for interstellar transportation. A global aerospace initiative aims to launch the construction of a lunar colony housing 100,000 people by 2050, a project requiring the transportation of 100 million tons of construction materials. Moreover, the sustainable supply of water and other materials must be ensured once the colony is operational. How to select the optimal transportation scheme under the multiple constraints of cost, time and environmental impact has become a core problem to be solved. Chen Hao et al. (2019) proposed a partially periodic time-expanded network method for regular interplanetary transportation mission planning, which is computationally scalable and reduces the initial mission mass in low Earth orbit[1]; Zhu Xiongfeng et al. (2022) put forward a top-level framework for launch and transportation systems, including a "five-in-one" composition, five specifications and five-generation standards, improving the industry soft environment[2]; Fiore Ilaria P. et al. (2024) explored lunar habitat development, emphasized in-situ resource utilization (ISRU) and AI, and noted AI's role in optimizing lunar transportation[3]; Zhang Zhenhua et al. and Chen Chin S. et al. (2025) respectively proposed a China's cargo spacecraft development plan (providing a reference for deep space exploration) and a Pareto front-based multi-objective optimization method for transportation (significantly improving scheduling efficiency [4][5]. However, existing research lacks targeted exploration on lunar colonization transportation planning, fails to combine Pareto optimization with Monte Carlo simulation to solve its multi-objective optimization under uncertainties, and insufficiently coordinates lunar habitat construction with transportation planning. Thus, this study focuses on lunar colonization transportation system planning, uses Pareto optimization and Monte Carlo simulation to establish a planning model, balance transportation objectives, handle uncertainties, and coordinate related transportation links, providing a scientific decision-making basis for sustainable lunar colonization.

2. Research on Transportation Schemes of Lunar Base Construction Materials Based on the Bi-objective Optimization Method

2.1. Objective Function

To better evaluate cost and time, the weighted sum method is adopted to convert the multi objective problem into a single-objective one. The core objective is to minimize the total cost and time, while constraints are imposed to ensure the feasibility of the schemes.

$$\min Z = \alpha \cdot \frac{C_{\text{total}}}{C_{\max}} + \beta \cdot \frac{T_{\text{total}}}{T_{\max}} \quad (1)$$

Where: Z is comprehensive utility score (smaller values indicate better performance), used to quantify the combined performance of cost and time, C_{total} is total transportation cost, T_{total} is total transportation time. The weights are specified as $\alpha = 0.6$ and $\beta = 0.4$, assigning higher priority to cost than time, which aligns with the emphasis on budget constraints in engineering practice.

2.2. Space Elevator Only

In this scenario, all construction materials are transported by the space elevator system (Galactic Harbor). The space elevator system consists of three Galactic Harbors uniformly distributed along the equator.

The total required quantity of materials is set as M_{total}= 100000000 tons. All construction materials are transported by the space elevator system (Galactic Harbor), so all considerations of cost and time are centered exclusively on the space elevator.

The cost of the space elevator consists of the initial construction cost and the subsequent operating cost. The construction cost is composed of the raw materials required to build the space elevator. To prevent the cable from breaking under its own weight and maximize material utilization efficiency, the cross-sectional area must be adjusted exponentially with altitude, which is expressed as follows:

$$A(r) = A_0 \exp\left[\frac{\rho}{\sigma}\,\mathrm{GM}\left(\frac{1}{R_e} - \frac{1}{r}\right) + \frac{1}{2}\omega^2\left(R_e^2 - r^2\right)\right] \quad (2)$$

Operating costs mainly consist of electricity costs during operation. It should be noted that maintenance costs for the space elevator cannot be neglected in actual operation either.

Finally, the total cost for the scenario using only the space elevator is obtained by summation, as shown in the following equation:

$$\text{Construction Cost(CAPEX)} = C_{\text{R\&D}} C_{\text{devolpment}} \left(\int_{R_e}^{R_t} A(r)\rho P_m dr\right) \quad (3)$$

$$\text{Operating Cost(OPEX)} = \mathrm{T}\cdot \mathrm{T}_{\text{maint}} + \mathrm{M}\cdot E_{\text{Unit}} \mathrm{P}_{\text{energy}} \quad (4)$$

$$C_{\text{SE}} = \text{CAPEX} + \text{OPEX} \quad (5)$$

Through calculation, The paper obtain the total cost under this scenario:

In the scenario where only the space elevator is employed, the annual throughput of the space elevator can be readily obtained through calculation.

$$T_{\text{SE}} = \frac{M_{\text{total}}}{Q_{\text{E}}} \quad (6)$$

From the analytical and computational results, it can be concluded that: The construction period of the space elevator-only scheme is 186.22 years, with a total cost of \$ 4.97 $\times 10^{11}$.The result is shown as Figure 1.

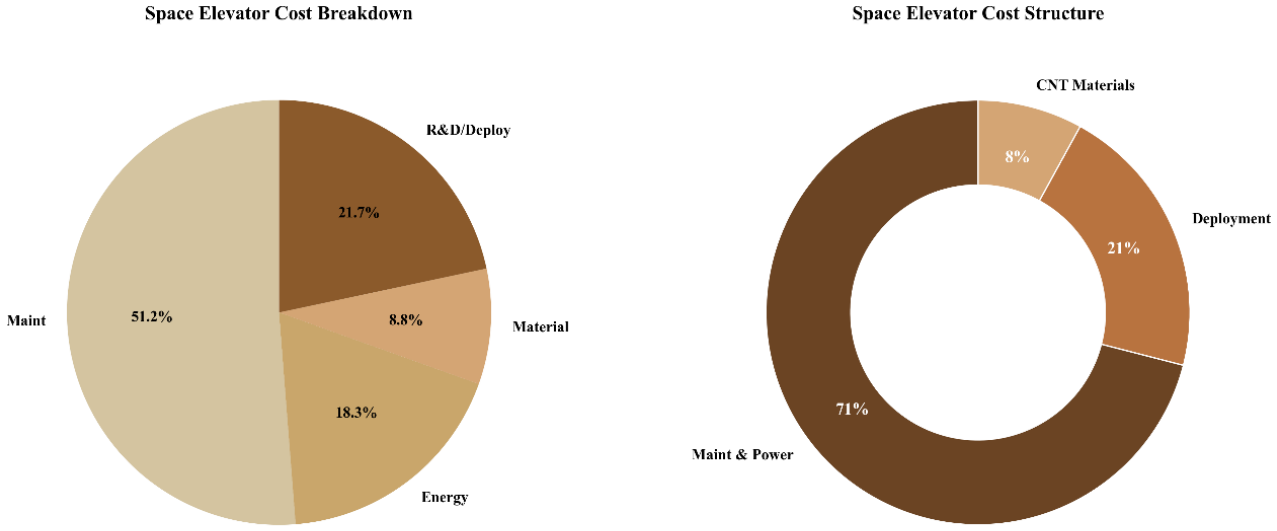


Figure 1: Elevator cost combined fixed

2.3. Rocket Only

In this scenario, all construction materials are transported via conventional rocket launches. The conventional rocket launch system is mainly composed of ten major rocket launch sites, with a total of 22 launch sites. Meanwhile, the Falcon Heavy rockets deployed in transportation are reusable, and the reusable cost is derived using the Wright learning curve model:

$$\alpha = -\log_2 k \quad (7)$$

Each rocket launch involves operational procedures including launch site depreciation, meteorological support, search and rescue recovery [6], among others, which inevitably generate the operational cost [7] C_{op}. Finally, the following equation is obtained by summation:

Finally, the following equation is obtained by summation:

$$C_{\text{TR}} = \int_1^N C_{\text{base}} \cdot x^{-\alpha} dx + N \cdot \left(C_{\text{fuel}} + C_{\text{refurb}} + C_{\text{ops}}\right) \quad (8)$$

In the scenario using only conventional rocket launches, the total launch time is determined by the total number of launches $N = \frac{M}{m_{\text{total}}}$ and the launch frequency f_{launch}. Rocket launches are typically conducted once per week, and the total time can be finally calculated as $\mathrm{T} = \frac{N}{f}$. From the analytical and computational results, it can be concluded that: The construction period of the rocket-only scheme is 86.32 years, with a total cost of \$3.16 × 10^{12}. The result is shown as Figure 2.

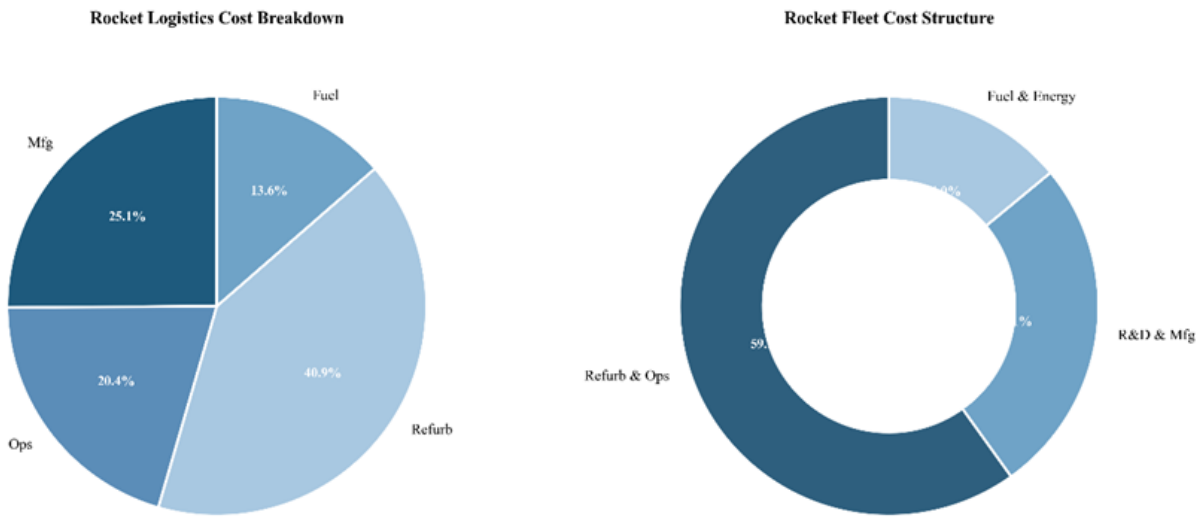


Figure 2: Rocket cost combined fixed

2.4. Hybrid Scenario

The hybrid transportation mode integrates the long-term economic efficiency of the space elevator and the short-term timeliness of rockets. Synchronized transportation is adopted to shorten the construction period of the lunar colony, while controlling the total cost. To better grasp and trade off the relationship between cost and time and determine the optimal hybrid transportation ratio, we introduce a decision variable.

Let the hybrid ratio α $(0 < \alpha < 1)$ represent the proportion of cargo transported by the elevator relative to the total freight volume. Then the freight volume of the elevator is $\alpha \cdot M_{\text{total}}$ and the freight volume of the rockets is $(1-\alpha)M_{\text{total}}$.The cost of the hybrid scheme is determined by the introduced decision variable. This cost covers the full construction cost of the space elevator, plus the operating costs of both the elevator and the rockets, while accounting for the rocket learning curve effect, The formula is given by:

$$C_{\text{total}} = C_{\text{SE,CAEPX}} + \alpha\, M_{\text{total}} \cdot C_{\text{SE,OPEX}} + (1-\alpha)\, M_{\text{total}} \cdot C_{\text{R,Unit}} \cdot k \exp \log_2\left(\frac{(1-\alpha)M_{\text{total}}}{m_{\text{Payload}} \cdot N_{\text{site}}}\right) \tag{9}$$

The construction period required by the hybrid scheme follows critical path logic. The total construction period is determined by the slower transportation link, and therefore takes the maximum value of the time consumed by the elevator and rockets to complete their respective transportation tasks:

$$T_{\text{total}} = \max\left(\frac{\alpha M_{\text{total}}}{Q_{\text{E}}}, \frac{(1-\alpha)M_{\text{total}}}{Q_{\text{R}}}\right) \tag{10}$$

The study reveals a trade-off between the cost and construction period of transportation schemes: reducing cost may lead to a longer construction period, while shortening the construction period may result in higher cost, and there is no single optimal solution that achieves both the absolute minimum cost and the shortest time.

To address this issue, Pareto frontier [8] analysis is employed to screen out non-dominated solutions. Combined with Pareto frontier analysis to filter non-dominated solutions, the optimal hybrid ratio is finally determined as shown in the figure 3 below:

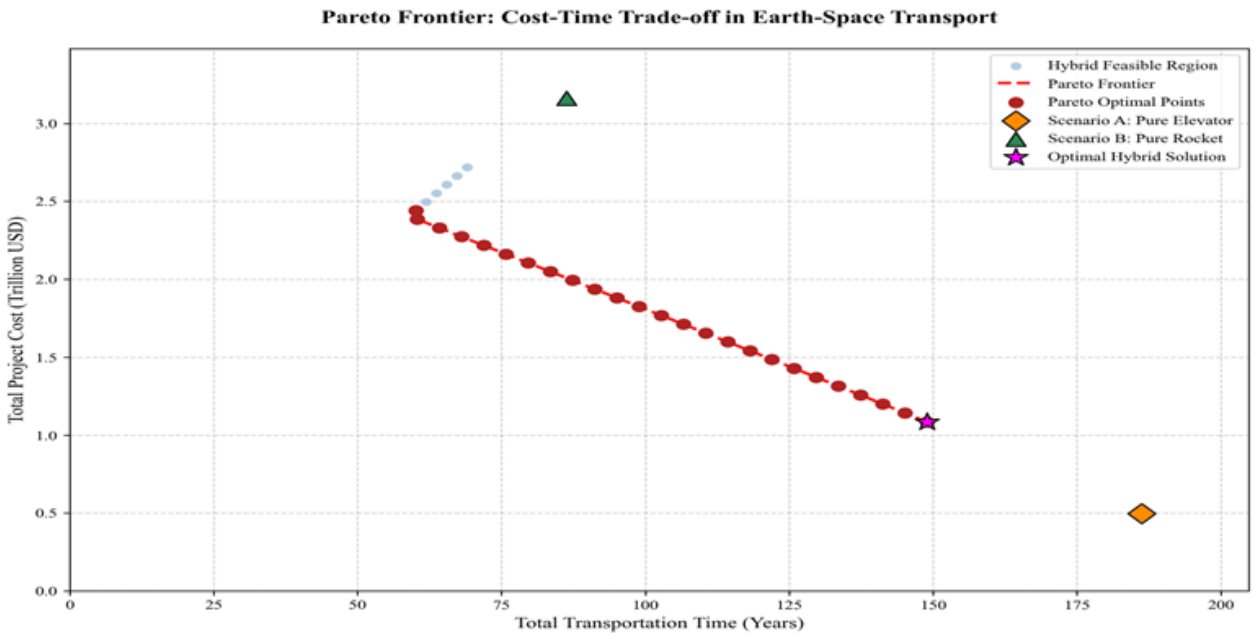


Figure 3: Pareto Frontier: Cost-Time Trade-off in Earth Space Transport

The red dashed line represents the optimal solution set, which refers to the schemes where the time cannot be shortened without increasing the cost, nor can the cost be reduced without increasing the time. The purple pentagram marks the globally optimal hybrid scheme calculated based on the utility function: 80.0% elevator / 20.0% rocket.

The paper summarize the comprehensive performance as follows: Total cost: $\$1.08 \times 10^{12}$,delivery time: 148.98 years.

Compared with the rocket-only scheme, the cost is reduced by 65.7%; compared with the elevator-only scheme, the construction time is shortened by 20.0%. The strategic roadmap and strategic performance are shown below Figure 4:

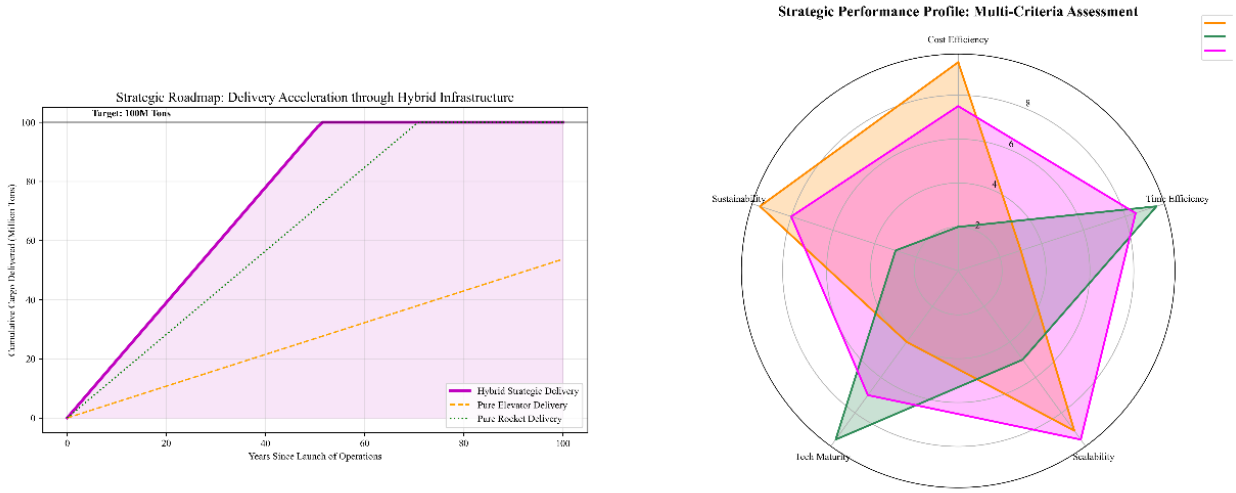


Figure 4: Timeline Radar Combined

3. Research on the Impacts of Transportation System Fault Scenarios Based on the Monte Carlo Simulation Method

Non-ideal factors in actual transportation are unavoidable, such as tether sway and structural failure of the space elevator, as well as launch failures and ad-hoc adjustments of rockets. Accordingly, this study establishes a fault model and adopts the Monte Carlo simulation method to quantify the impacts of different fault scenarios on transportation objectives, and proposes adaptive adjustment strategies.

3.1. Fault Scenario Design

Based on the system characteristics of the space elevator and rocket launch, four categories of fault cases are designed, ranging from single-point faults to composite faults. The trigger conditions, probability distributions, and impacts of each case are presented in the following table 1.

Table 1: Impact Analysis of Different Fault Scenarios

Scenario	Description	Variable Probability Basis	Throughput Impact	Cost Impact
S_1: Elevator Fault	Rope swing, power fluctuation	Normal distribution N(65%,5%), based on vibration frequency simulation	Reduced to 60-70%	Medium
S_2: Rocket Fault	Launch failure, weather delay	Normal distribution N(80%,5%), based on launch success rate statistics	Reduced to 75-85%	Medium
S_3: Mixed Fault	Simultaneous degradation of multiple subsystems	Composite probability distribution of S1 & S2	Extremely High	High
S_4: Extreme Fault	Catastrophic structural/logistics failure	Left-skewed distribution (Skewness = −5), mean 45%	Critical Impact	Extremely High

3.2. Objective Function Under Interval Uncertainty

Only capacity degradation is considered in fault scenarios, making the parameter intervals more reasonable. Based on the bi-objective optimization model from the first problem, the capacity degradation coefficient induced by faults is introduced. Consequently, the original cost and time objective functions need to be reformulated into interval forms to reflect interval uncertainty. Total Transportation Cost f_1(Interval):

$$f_1 \in [\max(f_{1,\text{base}} \times (1 + \alpha_{\min}), f_{2,\text{base}} \times (1 + \alpha_{\max})] \quad (11)$$

where a denotes the fault cost premium coefficient, with its interval determined according to different scenarios: single fault α ∈ [0.05,0.15], hybrid fault $\alpha \in$ [0.15,0.30], and extreme fault α ∈ [0.30,0.50] (based on aerospace emergency response data). Total Transportation Time f_2 (Interval):

$$f_2 \in [\max\left(\frac{\alpha \cdot 10^8}{C_{e,\min}}, \frac{(1-\alpha)\cdot 10^8}{C_{r,\min}}\right), \max(\frac{\alpha \cdot 10^8}{C_{e,\max}}, \frac{(1-\alpha)\cdot 10^8}{C_{r,\max}})] \quad (12)$$

where $C_{e,\min}$ and $C_{e,\max}$ are the lower and upper bounds of the interval for elevator transportation capacity after faults, and $C_{r,\min}$ and $C_{r,\max}$ represent the interval of rocket transportation capacity. The logic is that the lower the transportation capacity, the longer the time consumed, and the upper bound of the interval corresponds to the worst-case scenario.

3.3. Robustness Evaluation Model

3.3.1. Construction of the Evaluation System

The paper adopt the weighted performance degradation rate as the evaluation index. Considering the differences in risk preference under different scenarios, we define two sets of weighting systems: one being "Normal Weighting":

$$R = 1 - (0.6 \times \Delta\text{Cost} + 0.4 \times \Delta\text{Time}) \quad (13)$$

which is used for conventional evaluation, with an emphasis on budget control for large-scale infrastructure projects. And the other "Resilience Weighting":

$$R = 1 - (0.4 \times \Delta\text{Cost} + 0.6 \times \Delta\text{Time}) \quad (14)$$

which is used for sensitivity analysis under extreme faults, reflecting that when the system is damaged, the priority of schedule preservation is elevated over marginal cost.

To quantify robustness herein, the following indicators are defined. The first is "Cost Deterioration Rate(ΔC)": $\Delta C = \frac{C_{\text{fault}} - C_{\text{ideal}}}{C_{\text{ideal}}} \times 100\%$, where C_{ideal} is the cost under the fault-free scenario; The second is "Time Delay Rate(ΔT):" $\Delta T = \frac{T_{\text{fault}} - T_{\text{ideal}}}{T_{\text{ideal}}}$, where T_{ideal} is the time under the fault-free scenario; The third is "Robustness Score(R)": $R = 1 - (\omega_c \cdot \Delta C + \omega_T \cdot \Delta T)$, where the weights ω_c and ω_T reflect the decision-making preferences.)

3.3.2. Monte Carlo Simulation Method

To evaluate the degree to which our solution varies when the transportation system operates under non-ideal conditions, we conducted a stochastic robustness analysis using Monte Carlo simulation (N=50000). Meanwhile, we check whether the system satisfies the reliability constraints, where R_e and R_r denote the reliabilities of the subsystems. Samples that fail to meet the constraints are labeled as "failure", thereby enhancing the credibility of the Monte Carlo simulation. The simulation results with a mixing ratio α = 0.8 and the baseline weights are shown in the Table 2.

Table 2: Scenario Impact on Cost, Time and Robustness

Scenario	Avg. Cost Deterioration	Avg. Time Delay	Robustness Score (Baseline)
Elevator Fault (S_1)	+24.4%	+54.2%	0.637
Rocket Fault (S_2)	+25.8%	+0.0%	0.845
Mixed Fault (S_3)	+47.5%	+37.6%	0.564
Extreme Fault (S_4)	+171.1%	+188.1%	-0.779

As can be seen from the table, the robustness score of rocket fault (S_2) is the highest at 0.845, indicating the strongest system stability. The score of elevator fault (S_1) is 0.637, and that of hybrid fault (S_3) is 0.564, both of which fall within the controllable range. The robustness score of extreme fault (S_4) is -0.779, suggesting a collapse of system performance that requires the activation of the emergency plan.

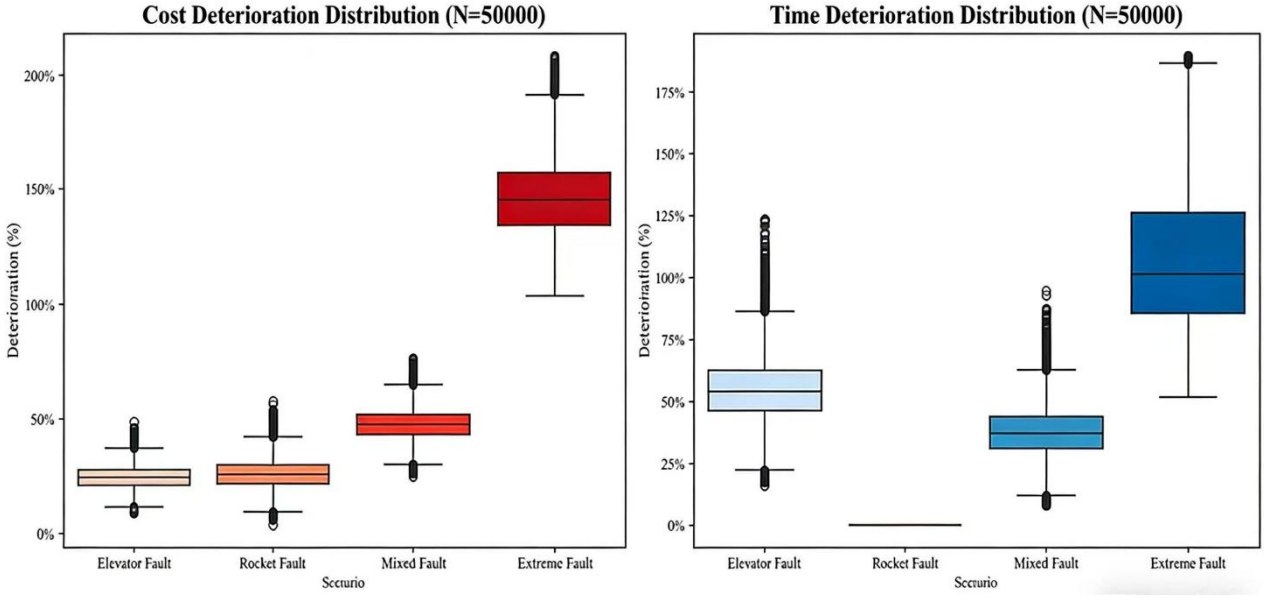


Figure 5: Performance Degradation Distribution Diagram

To visualize the impact of system faults more intuitively, we plotted the nonlinear effects of faults on system objectives and robustness impacts which are shown in Figure 5 under different scenarios. Based on the analysis of these figures, we can adjust our transportation strategy and further identify the optimal one.

4. Research on Lunar Base Water Demand and Transportation Schemes Based on Regression Prediction and MOEA/D

A regression and multi-objective optimization [9] framework is developed to predict water demand, evaluate cost and time, and determine the optimal water transportation scheme.

4.1. Regression Prediction Model

Following systems engineering principles, annual water resupply demand is categorized into life support, industrial production, and safety redundancy. Life-support water demand depends primarily on population (X_1) and per capita consumption (X_4), while industrial water demand (X_3) is determined by the production–domestic water use structure. Accounting for water recycling technology [10], higher recycling efficiency (X_2) reduces the growth of industrial water demand. The model is formulated as follows:

$$Y= \beta_0+ \beta_1X_1+\beta_2X_2+\beta_3X_3+ \beta_4(X_2+X_3) \quad (15)$$

Notation: $=\beta_0$ (constant term, basic water redundancy), $\beta_1 - \beta_4$ (regression coefficients) $\in$ random error, following $N(0,\sigma^2)$.

However, in practical scenarios, relevant authorities usually reserve a portion of water as emergency redundancy to prevent contingencies. With s denoting the emergency redundancy ratio ($0.05 \le s \le 0.2$) set aside as an emergency water source, the final planned quantity is given by

$$Y_{planned}=\widehat{Y}\times(1+s) \quad (16)$$

with a 95% confidence interval:

$$Y_{\text{planned}} \in [\hat{Y}(1+s) - 1.96 \times \text{RMSE}\,, \hat{Y}(1+s) + 1.96 \times \text{RMSE}] \quad (17)$$

Through model solution, the annual total water replenishment demand for a lunar colony with 100,000 residents is 269,746 tons (approximately 270,000 tons). The breakdown of demand by module is as follows: 60% for domestic water(161848 tons), 30% for production water(80924 tons), and 10% for emergency redundancy(26, 974 tons).

4.2. MOEA/D-based Multi-objective Optimization Model

After obtaining the annual total water replenishment demand in the previous section, to further better evaluate the water transportation cost and time, we still adopt the weighted sum method to transform the multi-objective problem into a single-objective one, and employ constraint conditions to ensure the feasibility of the solution.

$$\text{mingi}(x, K_w, s) = \lambda_{i1}f_{1M} - f_{1m} - f_1 + \lambda_{i2}f_{2M} - f_{2m} - f_2 \quad (18)$$

Where weight vector $\lambda_i = (\lambda_{i1}, \lambda_{i2})$, $\lambda_{i1}+\lambda_{i2}= 1$, f_{1m} and f_{1M} are minimum and maximum cost, and $f_{2m}$and f_{2M} are minimum and maximum time.

For transportation cost, based on the calculations in Chapter 2, we only discuss the transportation cost of water resources here. Since water resources must be transported in dedicated containers to prevent leakage, their transportation cost is λ times that of construction materials (λ > 1). The total transportation cost is thus obtained as:

$$f_1=x\cdot Y\cdot\lambda C_e+(1-x)\cdot Y\cdot\lambda C_r+k_w\cdot C_{batch} \quad (19)$$

Notation: C_e: Unit cost of the space elevator, C_r: Unit cost of the rocket, C_{batch}: Preparation cost per rocket batch.

The time cost is determined by the maximum duration between the rocket transportation scheme and the space elevator scheme. The space elevator operates in regular year-round ser vice with a transportation time of 1 year, while the delivery time of the last batch transported by rocket is $k_w 365$ (where k_w denotes the number of transportation batches). Thus,

$$f_2 = \max\{365, k_w 365\} = k_w 365 \quad (20)$$

(since $k_w > 1$) in practical transportation scenarios, the mission is subject to the following four constraints: Capacity constrain: $x \cdot Y \le C_{e,\text{remain}} = C_{e,\text{total}} \times (1 - x_{\text{material}})$ (where $C_{e,\text{total}}$ is the annual total capacity of the space elevator, and x_{material} is the capacity proportion occupied by construction materials.);Load Constraint: $k_w(1-x)\cdot Y \le Q_{\max}$(where $Q_{\max}$ is the maximum lunar payload of Falcon Heavy.); Reliability constraint: $\frac{R_e C_{e,\text{remain}}}{x \cdot Y} \times R_r^{k_w} \ge 0.95$ (where R_e is the annual reliability of the space elevator, and R_r is the single-batch reliability of the rocket); Variable constraints: $0 \le x \le 1, k_w \in \{1,2,\ldots,12\}, 0.05 \le s \le 0.2$.

Finally, the Pareto optimal solution set is output. Solutions are extracted according to three distinct criteria: optimal cost, optimal time, and balanced optimum, as presented in the table 3 below.

Table 3: Scheme Comparison Table

Strategy Type	Elevator Share	Rocket Launches	Additional Cost (Billion USD)	Delivery Completion Time (Days)	Strategy Characteristics
Minimum Cost	33.18%	1,215	11.41	365.0	Maximizes use of low cost elevators, suitable for regular operations
Fastest De livery	10.43%	14,976	15.68	115.4	Sacrifices cost for speed, ideal for emer-gency short ages
Balanced Optimum	33.18%	2,058	11.45	365.0	Optimizes transport rhythm with minimal cost increase

The left plot illustrates the objective law of trading money for time. The point in the upper-left corner represents the economy-oriented scheme, while the point in the lower-right corner denotes the emergency-oriented scheme. Decision-makers can select the optimal equilibrium point along the frontier curve according to fiscal conditions and safety requirements.

The right plot compares the supply intensity of different strategies. The fast-delivery scheme (orange line) can accomplish the annual mission within 115 days, which implies that the annual safety stock level can be established within the first one-third of the operation period. This significantly improves the risk-resistant redundancy of the colony, as shown in Figure 6.

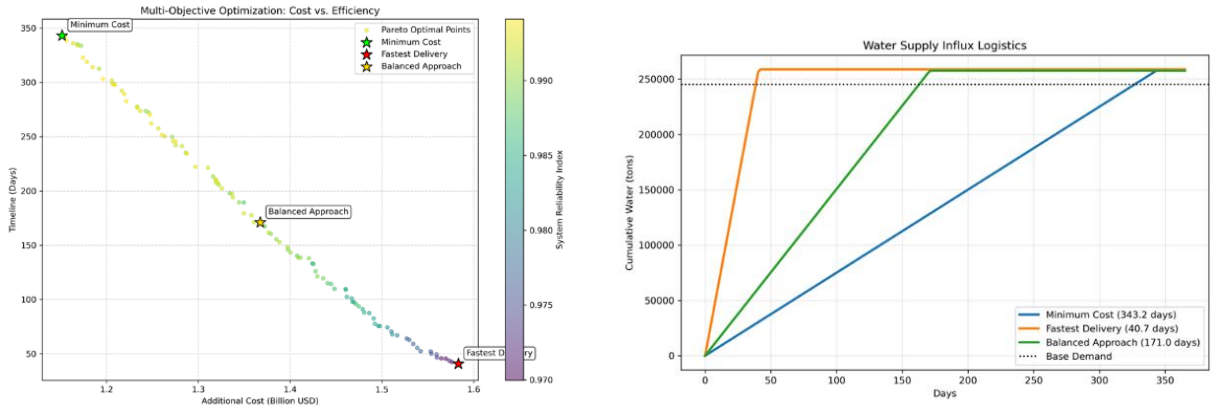


Figure 6: combined Pareto & timeline

5. Conclusion

Based on the mathematical model and solutions, we quantitatively analyzed lunar colony logistics. Under ideal conditions, static comparisons of three schemes show the pure space elevator is vastly superior in time, cost, and environmental impact, with a construction period of 186.22 years, total cost of 4.97×10^{11}. The pure rocket scheme takes 86.32 years, costs 3.16×10^{12}. While the hybrid scheme shortens construction to 148.98 years, its cost (1.08×10^{12})render it economically non-optimal.

When stochastic reliability factors are introduced for dynamic analysis, the system performance degrades significantly. Monte Carlo simulations show that the fluctuation of the time delay rate is small, indicating high operational stability, while the base cost is subject to more severe stochastic disturbances. Under reliability constraints, the project duration of the hybrid scheme is extended to 179.4 years, and the total cost increases to $\$1.3014\times10^{12}$. This implies that ap proximately 30.42 years of buffer time and a contingency budget of about $221.4 billion must be reserved in practical implementation to mitigate risks arising from uncertainties.

During the colony operation phase, the annual water demand is 269,746tons, totaling 13,487,300 tons over 50 years. Cost comparisons show the space elevator scheme holds a full-life-cycle eco nomic advantage, while the rocket scheme excels in time efficiency. A scheme with a 54.08% elevator proportion offers superior full-life-cycle reliability. Thus, the space elevator enables large scale material transport in the construction phase and provides an efficient, low-cost channel for later operational resupply.

References

[1] CHEN H, LEE H W, HO K. Space transportation system and mission planning for regular interplanetary missions [J]. Journal of Spacecraft and Rockets, 2019, 56 (1): 12-20.

[2] Zhu Xiaofeng, Cheng Hongwei, Liu Yang, etc. Top level planning and design of launch transportation system and countermeasures suggestions [J]. Industrial Technology Forum, 2022, 21 (15): 221-222

[3] FIORE I P, CORREA M, KARBALAEE M M, et al. Innovations and challenges in lunar habitat development: A sustainable future on the Moon through the use of artificial intelligence (AI)[C]//Proceedings of the International Astronautical Congress: 35th IAA Symposium on Space and Society, 75th International Astronautical Congress (IAC 2024). 2024: 698-700.

[4] Zhang Zhihong, Feng Yang, Bai Mingsheng. Research on the Development and Planning of Space Freight Transport System [J]. Spacecraft Engineering, 2025, 34 (6)

[5] CHEN C S, LIN C J, LIN Y J, et al. Application of multi-objective optimization for path planning and scheduling: The edible oil transportation system framework [J]. Applied Sciences (Switzerland), 2025, 15 (15): 1-14.

[6] PRANDTL L. Fluid motions with very small friction [C]//Proceedings of the 3rd International Mathematical Congress. Heidelberg: H. Schlichting, 1904: 484-491. ([A7.1])

[7] REN W, GE F, CHEN D, et al. A many-objective evolutionary algorithm based on decision variable classification mutation and indicator [J]. The Journal Supercomputing, 2025, 81 (14): 1293-1312.

[8] Zhu Xiongfeng, Liu Yang, Liu Ying, etc Research on the Launch Cost of Falcon 9 Launch Vehicle [J]. International Space, 2023 (11): 35-40

[9] AMRA A Z Y, MAGHARI Y A. Prediction of Nanofluid Specific Heat Capacity using Supervised Regression Models [J]. Journal of Engineering Research and Reports, 2025, 27 (10): 64-73.

[10] Yang Songlin, Ding Ping, Zhao Jiancheng, etc. Key Technology Analysis of Water Recovery System in China's Space Station [J]. Aerospace Medicine and Medical Engineering, 2013, 26 (3): 221-226