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ABSTRACT

The lunar base is a core strategic pivot for human deep space exploration, and building a large-scale, low-cost Earth-Moon transportation system is the core prerequisite for space colonization. Currently, neither the mainstream conventional rocket transportation mode nor the cutting-edge space elevator solution can meet the dual constraints of cost and construction period, which is a key planning challenge for future lunar base construction. Existing Earth-Moon logistics research has not established a unified quantitative optimization framework for rocket-space elevator hybrid transportation, lacks systematic performance comparison of three mainstream transportation strategies, and cannot realize global multi-objective collaborative optimization of full-cycle transportation cost and construction period. To address this research gap, this paper constructs a unified analysis framework of three mainstream transportation schemes with a dual-objective optimization model for total full-cycle cost and construction period, and adopts NSGA-Ⅱ algorithm and TOPSIS method for optimal solution screening and comprehensive scoring. The results show that the hybrid transportation mode achieves 38% cost reduction compared with the pure rocket scheme under balanced decision-making, and obtains better comprehensive performance than single schemes under different optimization preferences. This study effectively solves the core problem of collaborative optimization of Earth-Moon logistics cost and construction period, and provides quantitative decision support for lunar base transportation strategy formulation and reference for deep space exploration mission planning.

KEYWORDS

multi-objective optimization, earth-moon space transportation, space elevator, NSGA-II algorithm

INTRODUCTION

The lunar base constitutes a core strategic foothold for human deep-space exploration and serves as a key platform for validating extraterrestrial survival technologies and conducting space-based scientific observations. As the world's major spacefaring nations have successively unveiled their plans for lunar bases and the International Lunar Research Station, the Moon has thus become a central strategic priority in the domain of space exploration [1]. Consequently, a well-established, large-scale, low-cost Earth-Moon transportation system is an indispensable prerequisite for achieving the Resource exploration and space colonization. However, the construction of a large-scale lunar base faces formidable logistical challenges in Earth-Moon transportation. According to projections by the International Academy of Astronautics, the annual demand for cargo transport in cislunar space will exceed 15,000 tonnes by the middle of this century [2]; this figure far exceeds the capacity of conventional launch vehicles. In response, the space elevator has been proposed by the academic community as a potential solution. Nevertheless, even assuming its engineering feasibility, a critical issue remains to be urgently resolved for future lunar base construction: how to scientifically allocate material transport tasks between rockets and the space elevator, so as to achieve an optimal trade-off between transportation cost and construction schedule.

Regarding the optimization of Earth-Moon logistics, existing studies have conducted relevant explorations from the perspectives of energy analysis, mission planning, and collaborative control [3], leading to the identification of two mainstream technical pathways: conventional rocket transportation and space elevator transportation. These studies have laid a theoretical foundation for the optimal design of Earth-Moon transportation systems. However, the current literature has not yet established a unified quantitative model that integrates both rocket-based and space-elevator-based transportation modes. Most existing work remains confined to the analysis of a single transportation mode and lacks a systematic characterization of their coordinated operation. Furthermore, a comparative assessment of different logistics strategies under a common analytical framework is still absent. Insufficient attention has been paid to the trade-off between the two key objectives of total lifecycle cost and overall project duration, which has led to a weak quantitative foundation for multi-objective optimization research on Earth-Moon logistics. These research gaps make it difficult to formulate specific decision-making schemes that balance cost, schedule, and reliability, and thus hinder the provision of systematic support for the selection of transportation strategies in lunar base construction.

To address the aforementioned research gaps, this paper develops a multi-objective optimization model for Earth-Moon logistics, aiming to provide a quantitative basis and theoretical support for the formulation of transportation strategies in lunar base construction. The main contributions of this paper are as follows. First, for the first time, a hybrid transportation mode combining rockets and a space elevator is incorporated into a unified multi-objective optimization framework, enabling direct trade-off and synergistic optimization between the two core objectives: total lifecycle cost and overall project duration. In addition, a combinatorial solution strategy is designed. This strategy employs the NSGA-Ⅱ algorithm with a fixed-length encoding scheme based on five-period dimensionality reduction, and adapts the algorithm to the characteristics of the Earth-Moon logistics scenario, thereby extending its applicability to the domain of space logistics. Finally, through comparative analysis of multiple scenarios, the core advantages of the hybrid transportation mode in balancing cost and schedule are revealed, yielding optimized solutions of engineering reference value for decision-making regarding lunar base transportation strategies.

RELATED WORK

Space Elevator Transportation Strategies

In the research field of space elevator transportation strategies, existing achievements have fully validated its superior propulsion efficiency over conventional rockets. Engel systematically analyzed the lunar transfer scheme based on space elevators, laying the theoretical foundation for cislunar transportation via space elevators [4]. Subsequent scholars have proposed approaches including adaptive neural network control and cooperative game optimization with regard to the stability control and multi-objective optimization of elevator-based transportation, realizing the trade-off between transportation efficiency and orbital stability [5]. Nevertheless, all current studies concentrate on the internal optimization of the single transportation mode of space elevators. They have neither integrated space elevators with conventional rockets into a unified system for collaborative scheduling design, nor taken into account the impact of transportation fault disruptions on transportation schedules.

Space Logistics Optimization Frameworks

In the research on optimization frameworks for space logistics, Chen and Ho first coupled mission planning with spacecraft design and proposed a mixed-integer nonlinear programming model, laying the foundation for quantitative analysis of cislunar logistics [6]. Subsequent studies have further expanded the optimization framework, resolved the modeling complexity of long-period missions, and improved the solution efficiency of large-scale models [7]. Domestic scholars have also refined the system-level design methods for cislunar transportation [2]. However, most existing frameworks are constructed based on the single transportation mode of conventional rockets, without integrating the space elevator system. In addition, there is generally a lack of bi-objective collaborative optimization design that considers both the full-cycle total cost and the overall project duration.

Solution Strategies for Transportation Optimization

NSGA-II is a key computational tool in comparative studies of multi-objective and transportation optimization. Verma systematically reviewed its applications in six core combinatorial optimization problems and established a standardized performance evaluation framework, providing theoretical references and practical guidance for its optimization and engineering applications [8]. In aerospace engineering, NSGA-II and its improved algorithms have been applied to key scenarios such as rocket multidisciplinary design and launch vehicle landing mechanism optimization [9-12]. However, few research has applied this algorithm to multi-objective optimization for space logistics transportation, and gaps remain in algorithm adaptation and verification for this complex scenario.

Contributions of Research

In summary, no complete research system exists for cislunar logistics transportation optimization. A unified optimization framework for space elevator-rocket hybrid transportation is lacking, making it hard to balance the bi-objective optimization of full-cycle total cost and project duration, and the NSGA-Ⅱ algorithm has few application cases in this field. To address these gaps, this paper constructs a unified multi-objective optimization framework for the hybrid transportation, improves the system-level optimization system, designs an NSGA-Ⅱ solution algorithm based on 5-cycle dimension-reduced fixed-length coding to adapt to long-period needs and fill the application gap, and conducts multi-scenario comparative experiments to quantify transportation strategy performance, providing quantitative support and theoretical basis for lunar base cislunar transportation strategy formulation.

METHOD

Logistics and Transportation System

Rocket Transportation Mode

Early space launch programs were shaped by the dual factors of the Cold War arms race and breakthroughs in aerospace technology. Despite the low absolute number of rocket launches, their growth rate was rapid. With the maturation of reusable rocket technology and the commercialization of the aerospace industry, launch demand is set to see explosive growth. However, from a macro perspective, there is an inherent upper limit to rocket launch activities: the number of rocket launches cannot maintain exponential growth indefinitely, and will inevitably be constrained by environmental factors including global launch site resources, orbital slot resources, and market demand, which will drive the annual rated launch frequency of rockets to asymptotically approach saturation eventually. Therefore, the growth trend of the global annual rated rocket launch frequency can be characterized by the logistic saturation growth model:

$$N_{SR}(y) = \frac{K}{1 + \left(\frac{K}{N_0} - 1\right) \cdot e^{-r\cdot(y-y_0)}} \tag{1}$$

Where y denotes the baseline year for model fitting ; $N_{SR}(y)$ represents the global rated number of rocket launches in year y; K is the saturation upper limit of the annual number of launches; N_0 is the actual global number of rocket launches in the baseline fitting year y_0 ; r denotes the average annual growth rate of the annual number of launches.

However, deviations between the actual number of rocket launches and the model-predicted values may arise due to factors including technological advancements and policy adjustments. To address this issue, a core continuous decision variable α_y is introduced, which represents the rocket launch intensity in year y, and is numerically equal to the ratio of the actual number of launches to the rated number of launches. Accordingly, the actual annual number of rocket launches N_y in year y can be expressed as: $N_y = \lceil \alpha_y \cdot N_{SR}(y) \rceil$, where $\lceil \cdot \rceil$ denotes the ceiling operator, which is adopted to ensure that the number of launches is a positive integer. Meanwhile, to further align with the actual operational conditions of rocket launches, the loss of rocket transport capacity caused by launch failures is taken into account. On this basis, the effective transport capacity of rocket transportation in year y under the rocket transportation mode, denoted as $Q_{R,y}$, is given by:

$$Q_{R,y} = N_y \cdot Load_r \cdot S_{BASE} \tag{2}$$

where S_{BASE} denotes the baseline success rate of rocket launches, and $Load_r$ represents the rated effective payload of a single rocket launch.

Space Elevator Transportation Mode

To accurately represent the engineering operational characteristics of the space elevator, shutdowns and maintenance resulting from cable deterioration and aging are taken into account. Accordingly, this study introduces a failure probability function $M(y)$ that varies with the total system operating time, and establishes a dynamic capacity calculation model based on series system reliability

The core structure of the space elevator is a carbon fiber cable system assembled from multiple spliced segments, and its failure behavior conforms to the typical characteristics of a series reliability system. The cable consists of hundreds of independent carbon fiber segments connected in series; the fracture of any single segment will cause the entire elevator system to shut down immediately and enter a repair phase. In engineering practice, only the fractured segment can be locally replaced during repair, while the remaining undamaged segments retain their original material aging state and accumulated fatigue damage. For a series system composed of a large number of independently aging components, localized repair does not alter the overall aging trend of the system. Consequently, after repair is completed, the failure probability of the entire elevator system is not reset to its initial state, but continues to increase along the $M(y)$ curve as the total operating time accumulates.

Based on the above engineering characteristics, this study defines the failure probability function $M(y)$ as the probability that a space elevator that has been in operation for a cumulative total of y years since its initial deployment will experience a cable fracture failure in year y+1. The specific expression of this function can be obtained by fitting the simulation results of the long-term aging behavior of carbon fiber cables. For the planning of an Earth–Moon logistics system spanning several decades, the focus of this study is on the long-term statistical average transportation performance of the system rather than the specific timing of any individual failure event. Therefore, adopting the annual expected effective transport capacity makes it possible to quantify the impact of failure risk on transportation capacity while maintaining sufficient engineering accuracy. Based on the foregoing analysis and after incorporating the failure risk, the total effective transport capacity of n space elevators in year y is given by:

$$Cap_{elev,y}(n) = n \cdot y_{elev} \cdot Cap_{unit} \cdot (1 - M(y - y_{base})) \tag{3}$$

where y_{base} denotes the baseline year of the project, y_{elev} is a 0-1 switch variable for the elevator scenario that enables unified modeling of the three transportation modes, and Cap_{unit} is the annual rated transport capacity of a single space elevator.

Multi-Objective Optimization Objective Function

Full-Cycle Total Cost Objective Function

The total life-cycle cost C_{tot} consists of two components: the cumulative launch cost of rockets and the total cumulative cost of space elevators. The cumulative launch cost of rockets equals the sum of the total annual rocket launch cost throughout the total project duration. The total cumulative cost of space elevators equals the sum of the construction cost of n space elevators $C_E(n)$ and the annual operational transport cost of n operating elevators during the project duration:

$$C_{tot} = \sum_{y_{base}}^{t_f} [Q_{R,y} \cdot C_{Rt}(y)] + [C_E(n) + \sum_{y_{base}}^{t_f} C_{op,y}(n)] \tag{4}$$

Where y_{base} denotes the baseline year of the construction period; $C_{op,y}(n)$ represents the transport cost of operating n space elevators in year y , which can be expressed as: $C_{op,y}(n) = C_{op} \times Cap_{elev,y}(n)$, where C_{op} is the unit transport cost per single space elevator; $C_{Rt}(y)$ is the unit transport cost per rocket in year y . Owing to the advancement of aerospace technology, this cost function exhibits a downward trend with the elapse of years. In the field of aerospace engineering, it is typically characterized by a cumulative launch volume-based learning curve model, which captures the cost reduction effect driven by the expansion of launch scale:

$$C_{Rt}(y) = C_{y_{base}} \cdot \left(\frac{N_{cum}(y)}{N_{SR}(y_{base})} \right)^b \tag{5}$$

where $C_{y_{base}}$ denotes the baseline unit transport cost of rockets in the baseline year y_{base} , $N_{cum}(y)$ represents the cumulative actual number of rocket launches up to year y , and b is the learning curve exponent.

Total Project Duration Objective Function

The total project duration is defined as the time span from the baseline year to the completion year when the cumulative effective transport capacity meets the total material demand for the first time. Its mathematical expression is: $T_{tot} = t_f - y_{base}$, where t_f is the completion year.

Solution Algorithm for the Optimization Model

Fixed-Length Coding Design for Decision Variables

To improve the solution efficiency and reduce the computational complexity, dimension reduction is performed on the decision variables in this project. Suppose the maximum project duration required to complete the project is T_{max} years, which is equally divided into x sub-periods. The value of the rocket launch intensity α_y remains unchanged within the same sub-period. The individual coding structure is defined as follows:

$$Individual = [n, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, ..., \alpha_x] \tag{6}$$

Where n is the number of constructed space elevators, which takes integer values in the set $\{0, 1, 2, 3\}$; α_1 to α_x denote the average rocket launch intensity α_y corresponding to the x sub-periods, respectively. The computation involving $T_{max} + 1$ decision variables is thus compressed into a simplified calculation with only $x + 1$ decision variables. This dimension reduction operation can effectively capture the overall variation trend of the launch intensity curve while filtering out minor fluctuations in launch intensity between individual years.

Solution Procedure of the NSGA-Ⅱ Algorithm

This paper adopts the Non-dominated Sorting Genetic Algorithm II with Elitist Strategy (NSGA-Ⅱ) to solve the above dual-objective optimization model, and designs an x-cycle dimension-reduced fixed-length coding scheme to address the problems of low solution efficiency and unfixed coding length in long-period optimization problems. The complete solution flowchart is shown as in Figure 1:

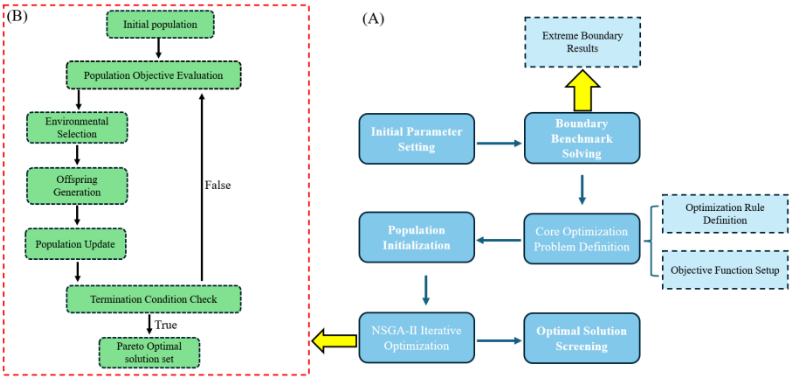

Figure 1. Flowchart of the Solution Algorithm for the Optimization Model

As shown in Figure 1 (A), the overall framework of model solving is presented. (1) the core benchmark parameters of the entire transportation project, including the total material transportation demand Q_{req} and the maximum project duration T_{max} , are fixed to establish a unified and reproducible calculation benchmark for the whole algorithm. (2) Subsequently, preliminary solution is performed on the benchmark boundary schemes, and the cost and duration of the two single transportation modes are calculated respectively, which serve as the upper and lower bounds of the model's optimization objectives and provide a comparison benchmark for the subsequent screening of optimal equilibrium solutions. (3) Based on the pymoo optimization framework, the Earth-Moon logistics transportation problem is transformed into a standard multi-objective optimization problem. To construct a solvable model framework, the basic specifications of the optimization problem are defined, including the decision variables, optimization objectives and constraints. Meanwhile, the calculation method of the objective functions is given to realize the output of objective function values. (4) The basic parameters of the initial population are set, including the population size N_{pop} , maximum number of iterations G_{max} , crossover probability P_c and mutation probability P_m . After that, the main program module is executed, and the Pareto optimal solution set is obtained by solving the model with the NSGA-Ⅱ algorithm. (5) Finally, the TOPSIS ideal point method is applied to the output Pareto optimal solution set to calculate the comprehensive evaluation score of each optimal solution, and the optimal scheme is obtained ultimately.

As shown in Figure 1 (B), the operational workflow of the NSGA-Ⅱ algorithm is presented. After fixing the relevant parameters of the initial population, the dual objective values (total life-cycle cost and total project duration) of each individual in the population are calculated first. Then, non-dominated sorting and Pareto rank classification are performed on the population: individuals are divided into different Pareto ranks according to the dominance relationship to screen non-dominated solutions, and the crowding distance of individuals within the same rank is calculated to ensure the distribution diversity of the solution set. Afterwards, an offspring population of the same size is generated through selection, crossover and mutation operations. The parent and offspring populations are then merged, and elite individuals are screened out based on the results of Pareto rank classification and crowding distance calculation to form a new generation population. When the number of iterations reaches the preset threshold, the output result is the optimal solution set of the model.

Pareto Optimal Solution Selection Criterion Based on TOPSIS Ideal Point Method

Through the NSGA-II algorithm described above, a set of non-dominated solutions distributed along the Pareto front is obtained. These solutions constitute a candidate solution set, in which each solution represents a trade-off between cost and duration that cannot be substituted for one another. To select from this set the final solution that best reflects the decision-maker's preferences, this paper introduces the TOPSIS ideal point method for comprehensive evaluation and ranking of the solutions. Specifically, the minimum total life-cycle cost and the shortest total project duration are taken as the positive ideal solution (PIS), while the maximum total life-cycle cost and the longest total project duration are taken as the negative ideal solution (NIS). The comprehensive evaluation score S is obtained by calculating the weighted Euclidean distance from each solution to the positive and negative ideal solutions. The closer the score is to 1, the better the comprehensive performance of the corresponding solution. The core formulas are as follows:

$$S = \frac{\sqrt{w_1 \cdot \left(\frac{C - C_{max}}{C_{max} - C_{min}}\right)^2 + w_2 \cdot \left(\frac{T - T_{max}}{T_{max} - T_{min}}\right)^2}}{\sqrt{w_1 \cdot \left(\frac{C - C_{min}}{C_{max} - C_{min}}\right)^2 + w_2 \cdot \left(\frac{T - T_{min}}{T_{max} - T_{min}}\right)^2} + \sqrt{w_1 \cdot \left(\frac{C - C_{max}}{C_{max} - C_{min}}\right)^2 + w_2 \cdot \left(\frac{T - T_{max}}{T_{max} - T_{min}}\right)^2}} \quad (7)$$

where: C_{min} , C_{max} denote the minimum and maximum values of the total life-cycle cost obtained from the preliminary solution, respectively; T_{min} , T_{max} represent the minimum and maximum values of the total project duration obtained from the preliminary solution, respectively; w_1 , w_2 are the weights of the cost objective and the duration objective, respectively, subject to $w_1 + w_2 = 1$.

EXPERIMENTAL DESIGN AND RESULT

Experimental Background

The background setting of this experiment refers to Problem B of the 2026 Mathematical Contest in Modeling (MCM) [13]. Specifically, it is considered to establish a lunar base suitable for long-term operation on the Moon after the baseline year $y_{base} = 2050$, which requires transporting a total of $Q_{req} = 10^8$ tons of materials to the lunar base. It should be noted that the transportation of 10^8 tons of materials is the material demand during the construction phase of the project, and does not include the ongoing operational supplies after the project is completed. Three transportation schemes are provided as follows:

- Pure Rocket Transportation Scheme: Only the Falcon Heavy Rocket with a rated effective payload of $Load_r = 125$ tons per rocket is used for transportation throughout the entire construction period.
- Pure Space Elevator Transportation Scheme: Only 3 equatorial space elevators ($n = 3$) are used for transportation throughout the entire construction period, where the annual rated transport capacity of each space elevator is $Cap_{unit} = 179000$ tons per year.
- Hybrid Transportation Scheme: Both rockets and space elevators are used for material transportation simultaneously throughout the entire construction period.

Constraints

To ensure the solvability of the model, additional constraints are further specified. First, for any transportation scheme, the cumulative effective transport capacity from the baseline year to the project completion year t_f must fully meet the total required material demand Q_{req} , which is expressed as:

$$\sum_{y_{base}}^{t_f} [Q_{R,y} + Cap_{elev,y}(n)] \geq Q_{req} \tag{8}$$

In addition, to ensure that the rocket launch decision complies with the actual boundary of global rocket production capacity and avoid significant deviation of the annual number of rocket launches from actual operational conditions, a hard constraint is imposed on the rocket launch intensity α_y in any year: $0 \leq \alpha_y \leq 2$, where the upper limit of 2 indicates that the actual number of launches shall not exceed twice the rated number of launches at maximum. Meanwhile, to avoid extreme jumps in annual launch intensity, a smoothness constraint on launch intensity is set: $| \alpha_y - \alpha_{y-1} | \leq 0.2$, where the allowable variation amplitude of 0.2 ensures that the number of rocket launches in consecutive years conforms to the practical law of capacity adjustment in the aerospace industry. To meet the solution requirements of fixed-length coding, a hard boundary for the endogenous completion year is set, with the maximum project duration $T_{max} = 200$. This value ensures the fixed and reasonable coding length of decision variables during the optimization process, and minimizes the computational complexity while guaranteeing the effectiveness of the solution. Finally, to realize the horizontal comparison of the three strategies (pure rocket, pure elevator, and hybrid transportation), scenario locking constraints are set as follows:

- Pure Elevator Mode: The rocket launch intensity $\alpha_y = 0$ is enforced for all decision years, and the number of constructed space elevators satisfies $n \geq 1$;
- Pure Rocket Mode: The number of constructed space elevators is enforced as $n = 0$, and the elevator scenario switch variable satisfies $y_{elev} = 0$;
- Hybrid Mode: The number of constructed space elevators satisfies $n \geq 1$, and the rocket launch intensity satisfies $\alpha_y \in [0, 2]$.

Experimental Parameter Settings

To ensure the solvability of the proposed model, this study explicitly specifies the values and setting basis of all core parameters, as detailed below: The baseline year for model fitting is $y_0 = 2024$. Based on the historical data of rocket launches from 1957 to 2024 after eliminating outliers, the actual global number of rocket launches in the baseline fitting year is $N_0 = 274$ launches, the average annual growth rate of the annual number of launches is $r = 0.04$, and the baseline success rate of rocket launches is $S_{BASE} = 0.89$ [14]. The baseline unit transportation cost of rockets in 2050, C_{2050} is determined to be 15,200 USD/kg through trend fitting of historical data from the aerospace database of the Center for Strategic and International Studies (CSIS) [15]. With reference to relevant research findings and in consideration of the iterative development trend of aerospace technology, the saturation upper limit of annual rocket launches under a conservative scenario is set to $K = 20,000$ [16]. The construction cost of a single space elevator is $C_E = 25$ billion USD, and the unit operational transportation cost of a single space elevator is $C_{op} = 40$ USD/ton. The above values are typical reference values for the construction and operational transportation links of space elevators [17,18]. Finally, for the NSGA-II algorithm adopted for optimization solving, the core parameters are set as follows: the initial population size $N_{pop} = 100$, the maximum number of iterations $G_{max} = 200$, the crossover probability $P_c = 0.8$, and the mutation probability $P_m = 0.1$. All the above parameters are typical values in the application of this algorithm, and their rationality has been widely verified in existing studies [8, 19]. According to Popescu's study, the fracture life of carbon fiber cables follows a Weibull distribution [20]. The corresponding hazard rate function represents the probability that an elevator that has been in operation for a cumulative total of y years will experience a cable fracture failure in year $y+1$. Accordingly, the expression for $M(y)$ is: $M(y)=0$ when the cumulative operating years $y-y_{base} \leq 50$, and $M(y)=\frac{2.1}{89.3}\left(\frac{y-3000}{89.3}\right)^{1.1}$ when $y-y_{base}>50$.

Experimental Results and Analysis

Algorithm Convergence and Stability

To verify the solution performance of the NSGA-Ⅱ algorithm with 5-cycle dimension reduction and fixed-length coding designed in this paper, prove the reliability of the algorithm's output results, and eliminate conclusion deviations caused by random iteration, optimization experiments with 200 to 600 generations of iterations were carried out respectively for the hybrid scheme under equal weights ($w_1=0.5, w_2=0.5$). Convergence analysis was conducted from the perspectives of the fluctuation range of the optimal solution and the stability of the Pareto front. The statistical results of convergence performance under different iteration numbers are listed in Table 1.

Table 1. Statistical Results of Algorithm Convergence Performance Under Different Iteration Numbers

Number of Iterations	Optimal Number of Elevators	Optimal Total Cost (Billion USD)	Optimal Period (Years)	Launch Intensity α
200	3	9499590.98	77	[1.677 1.784 1.597 1.617 1.563]
300	3	9651844.44	75	[1.918 1.907 1.904 1.921 1.830]
400	3	9651905.01	75	[1.878 1.920 1.744 1.824 1.933]
500	3	9727607.37	74	[1.963 1.999 1.827 1.887 1.897]
600	3	9728210.61	74	[1.976 1.995 1.873 1.855 1.704]

As can be observed from the statistical results in Table 1, the optimal decisions and core indicators generated by the model tend to stabilize with the increase in the number of iterations under different generation settings. After 400 generations of iteration, the total cost and construction period corresponding to the optimal solution are fully stabilized, indicating that the final decision results exhibit no significant random fluctuations. When the number of iterations is set to 600 generations, no further optimization of the output optimal decision results is observed, which demonstrates that the algorithm has reached its global optimal convergence state at 500 generations of iteration.

As shown in the convergence curves in Figure 2, the Pareto fronts obtained from 400 to 600 generations are almost completely coincident. No significant differences are observed in the distribution range, density of non-dominated solutions, and upper and lower boundaries among the three iterative fronts, indicating that the boundary of the solution set has stabilized and no superior extreme schemes have emerged. When the number of iterations exceeds 400 generations, the algorithm has identified the complete optimal solution set, and the Pareto front no longer expands or optimizes with increasing iterations.

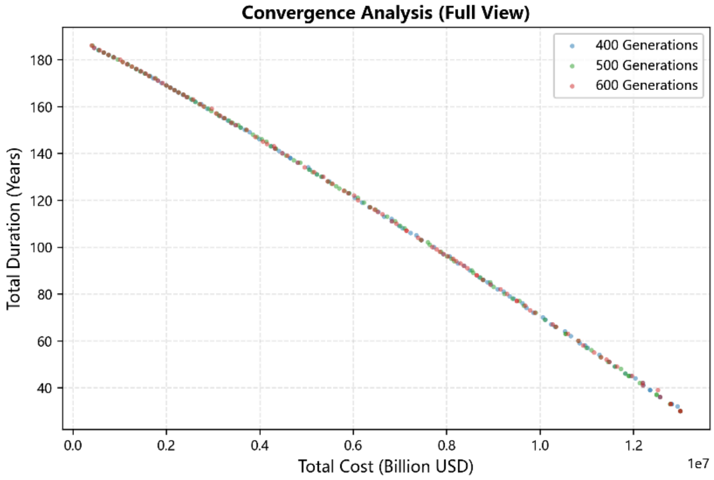

Figure 2. Pareto Front Curves with Different Iteration Numbers

In summary, this paper verifies from both the fluctuation range of the optimal solution and the stability of the Pareto front that the algorithm achieves global convergence and yields the optimal solution at 500 generations. In subsequent experiments, the solution process will be performed based on 500 iterations.

Comparative Analysis of Transportation Scheme Performance

To accommodate the differentiated optimization preferences for different objectives, three weight ratios are configured in the experiments: the balanced preferences scenario ($w_1 = 0.5, w_2 = 0.5$), the time-prioritized preference scenario (w_1=0.15, w_2=0.85), and the cost-prioritized preference scenario ($w_1 = 0.85, w_2 = 0.15$). The indicator results of the optimal solutions from five groups of experiments are listed in Table 2.

Table 2. Core Performance Comparison of Different Transportation Schemes

Decision Scheme	Number of Elevators	Full-Cycle Total Cost (Billion USD)	Duration (Years)	Duration Reduction Ratio	Cost Reduction Ratio
Cost-Prioritized	3	406842.96	187	0.53%	97.41%
Balanced	3	9727607.37	74	60.63%	38.09%
Time-Prioritized	3	9727607.37	74	60.63%	38.09%
Elevator-Only	3	401323.33	188	0%	97.44%
Rocket-Only	0	15714608.83	92	51.00%	0%

As can be seen from the results in Table 2, the two single transportation scheme, namely rocket-only and elevator-only, both face an inherent trade-off dilemma between cost and construction period, failing to simultaneously meet the dual engineering requirements of low cost and short construction period. In contrast, the corresponding hybrid transportation scheme can effectively balance the two objectives under different optimization preferences: under the cost-prioritized scenarios , the hybrid scheme achieves a cost roughly equivalent to that of the elevator-only scheme while slightly reducing the construction period; in the balanced and time-prioritized scenarios, the hybrid scheme not only breaks through the lower limit of the construction period of the rocket-only scheme, but also achieves an 38% cost reduction compared with the rocket-only scheme, demonstrating a significant advantage in comprehensive performance.

It should be noted that the optimal solutions of the time-prioritized scenario and the balanced scenario are clearly identical. This convergence is not coincidental: under the current model constraints—including the rocket production capacity saturation limit,the space elevator rated capacity, and the launch intensity bounds —74 years represents the rigid lower bound of the feasible construction period. When the optimization is driven by a balanced or time-prioritized weighting, the duration objective quickly reaches this physical limit. Beyond this point, no further reduction in construction period is possible, regardless of how much additional weight is assigned to the time objective. Consequently, while the balanced and time-prioritized scenarios reflect genuinely different decision-maker preferences at the problem formulation stage, they converge to the same optimal strategy at the solution stage, because the model's physical constraints leave no room for further trade-off in the time dimension. This convergence itself is a meaningful finding, it quantitatively identifies the hard duration bottleneck under current technological assumptions, and it indicates that decision-makers who prioritize time will all be guided toward this same cost-optimal, minimum-duration strategy.

Table 3 presents the comprehensive score S of the three transportation schemes under different preference requirements. From the data results, it can be observed that single transportation modes suffer from inherent deficiencies in decision-making adaptability. The rocket-only and elevator-only schemes only achieve high scores in single-preference scenarios matching their respective advantages, while their scores drop sharply under opposite preference conditions. Neither can balance the dual requirements of cost and time, making them unsuitable for complex engineering decision-making scenarios. In contrast, the hybrid transportation schemes demonstrates systematic performance advantages. Under the cost-prioritized scenario, it achieves a TOPSIS score comparable to the elevator-only scheme while offering a slight reduction in construction period. Under the balanced and time-prioritized scenarios, it attains substantially higher composite scores than either single mode, because it simultaneously delivers the shortest feasible construction period and significant cost savings relative to the rocket-only baseline. These results confirm that the hybrid transportation framework can generate superior transportation strategies under distinct decision-making preferences, providing robust quantitative support for Earth-Moon logistics planning.

Table 3. Comprehensive Score of Different Transportation Schemes

Scheme	Balanced	Cost-Prioritized	Duration-Prioritized
Rocket-Only	0.5000	0.2958	0.7042
Elevator-Only	0.5000	0.7042	0.2958
Hybrid Transportation	0.6636	0.7058	0.7936

Discussion on Engineering Feasibility

The above findings indicate that both the pure rocket and pure space elevator transportation modes entail costs and timelines that appear to fall beyond the reasonable scope of conventional engineering projects. It must be emphasized, however, that the object of this study is a large-scale lunar base requiring the delivery of 10^8 tonnes of material for its construction. By way of reference, NASA plans to deliver 64 tonnes of cargo at an estimated cost of 20 billion USD by 2032 to establish the first lunar base [21]. It is thus evident that the target scale of this study exceeds that of any current lunar base construction program by six orders of magnitude. An undertaking of this magnitude necessitates a concerted global effort, and the expenditure of funds on the order of hundreds of trillions to several quadrillion dollars and a timeline spanning several decades are inherent attributes of such a mega-project rather than a deficiency of the research design. A further feasibility assessment of the three transportation schemes yields the following observations. The pure rocket scheme, although capable of completing the delivery of one hundred million tonnes of material within a century, demands an excessively large investment and is therefore scarcely economically viable. The pure space elevator scheme, while offering substantially lower costs, entails a timeline approaching two centuries, which would chronically expose the entire construction project to external risks—such as economic crises, international political instability, and even armed conflict—leading to likely delays or outright disruption. In contrast, the hybrid transportation mode identifies an engineering-feasible equilibrium between these two extremes: without the excessive pursuit of unilateral cost advantages, it is capable of completing this massive-scale construction task within the shortest possible timeline and an acceptable cost range. This is precisely the core engineering value of the quantitative decision-support framework established in this study.

CONCLUSION

Addressing the core challenge of reconciling cost and construction duration in Earth–Moon logistics, this paper integrates rocket and space elevator transportation modes into a unified analytical framework, and establishes a bi-objective optimization model with total cycle cost and total project duration as the optimization objectives. By introducing a rocket launch intensity decision variable and a dynamic reliability model for the space elevator, the long-term evolution characteristics of the two transport capacities are characterized. An NSGA-II-based solution strategy is designed on this basis, achieving the globally coordinated allocation of the two transport capacities under the hybrid transportation mode. Experiments show that the hybrid transportation mode achieves a higher composite score than the single transportation modes. In particular, when the cost objective is not pursued to an extreme, the hybrid mode reduces the total cost by 38% compared with the pure rocket scheme and shortens the project duration by 60% compared with the pure space elevator scheme. effectively resolving the inherent conflict between cislunar logistics cost and duration. This work provides practical quantitative decision support for transportation strategy planning in lunar base construction.

The main contribution of this study to Earth–Moon logistics lies in the construction of a unified multi-objective quantitative optimization framework that enables the co-optimization of total cycle cost and overall project duration across both rocket and space elevator transportation modes. Based on this framework, the relative merits of the three transportation strategies under different decision-making preferences can be quantitatively assessed, and it was also proved that the hybrid transportation mode exhibits clear comprehensive engineering advantages over both single-mode alternatives, a finding that provides a replicable quantitative foundation for the strategic planning of future cislunar space infrastructure.

In future research, the study can be further deepened around the multi-dimensional constraint system of the Earth-Moon space logistics system, expand the boundary of multi-factor collaborative optimization for the whole process of Earth-Moon transportation, and explore the optimization potential of transportation strategies in complex deep space scenarios. Building upon the construction-phase optimization framework established in this paper, subsequent work can extend to the logistics required for sustainable lunar base operation, including regular resupply of consumables, spare parts, maintenance equipment, and emergency redundancy. The quantitative decision-making system for Earth-Moon space transportation will be continuously improved to provide more comprehensive theoretical support for the sustainable development of deep space exploration projects and the development and utilization of Earth-Moon space resources.

Author Contributions

Conceptualization – Liu Z H; methodology – Liu Z H; formal analysis – Liu Z H; investigation – Surname X; resources – Liu Z H; writing-original draft preparation – Liu Z H; writing-review and editing – Liu Z H; visualization – Liu Z H; supervision – Liu Z H. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The author declares no conflict of interest.

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Data Sharing Agreement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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