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**Summary**

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# Introduction

## Problem Background

In the deep space exploration era, sustainable lunar settlements are a core goal for global space agencies (NASA’s Artemis Program, ESA’s Moon Village) [1]. A large-scale, low-cost Earth-Moon cargo transport system is critical.

Current logistics rely on traditional heavy-lift rockets—direct and rapid but costly, low-frequency, limiting million-ton-scale transport. Emerging space elevators, enabled by materials/structural advances, offer low per-mass costs and near-zero pollution [2]. Yet rockets excel at oversized/emergency cargo, while space elevators face technical hurdles in materials, dynamic control, and orbital synchronization [3]. Lunar bases need massive construction material and continuous life support, requiring optimized hybrid architectures balancing cost, time, capacity, and reliability.

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|  |
| Fig.1 Earth-Moon Transport: Background Overview |

## Problem Restatement

Based on the given background, assumptions, and constraints, this paper evaluates alternative Earth–Moon transportation systems. The main objectives are to:

**Task1:** Model and compare the cost and delivery time of three transportation schemes: a space elevator system, a traditional rocket system with optimized launch site selection, and a hybrid system that allocates capacity by cargo type.

**Task2:** Analyze system resilience under non-ideal conditions, including capacity reduction and equipment failure, and propose adaptive strategies to mitigate disruptions.

**Task3:** Develop a continuous resupply plan for a lunar base by incorporating annual water demand and assessing long-term feasibility.

**Task4:** Evaluate and minimize environmental impacts by comparing rocket emissions and space elevator energy consumption.

**Task5:** Integrate all performance metrics to provide decision support and recommend an optimal transportation strategy with a phased implementation plan.

## Our Work

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# Assumptions and Justifications

**·Assumption 1: Characteristics of "Effective Capacity" and "Marginal Cost" for Space Elevators**

**Justification:** According to the Tsiolkovsky rocket equation, rockets must carry enormous amounts of fuel to overcome Earth's gravitational well, with costs primarily tied to fuel and vehicle depreciation. In contrast, space elevators rely mainly on electricity, and gravitational potential energy can be partially recovered.

**·Assumption 2: Heavy-Lift Rocket Cost Model and Launch Window Constraints**

**Justification:** Without a launch frequency limit, the model would yield the absurd conclusion that "millions of rocket launches could complete construction in a single year." This constraint reflects considerations of real-world bottlenecks in the aerospace supply chain, based on global launch site data over the past 15 years.

**·Assumption 3: Discretization and Time-Lag Simplification of Transport Processes**

**Justification:** The core of the problem is a macro-logistics plan for 100 million tons of cargo (spanning decades), where hour/day-level loading/unloading errors have an impact of order ϵ on the overall timeline.

**·Assumption 4: Neglect of Complex Real-World Social Conditions**

**Content:** We assume that all launch sites and Galactic Ports are centrally managed by the MCM organization, with no consideration of international political games, tariffs, or exclusive bidding between sites.

**·Assumption 5: Markov Property of Failures**

**Content:** We assume that the future state (normal/failed) of the system depends only on its current state, with failures occurring according to a Poisson distribution and a fixed failure repair time window.

假设Apex -月球段的火箭运输无失败风险。

# Notations

The key mathematical notations used in this paper are listed in Table 1.

Table 1: Notations used in this paper

|  |  |  |
| --- | --- | --- |
| **Symbol** | **Description** | **Unit** |
|  | Number of heavy rocket launches conducted at the k-th launch site in year ( = 1,2,…,10) | launches/year |
|  | Volume of supplies transported via the p-th space elevator port in year (= 1,2,3) | metric tons |
|  | Binary indicator for whether the project is completed (all supplies delivered) in year | N/A |
|  | Total supplies required for lunar colony construction, with a value of 108 | metric tons |
|  | Number of rocket launch sites | sites |
|  | Number of space elevator ports | ports |
|  | Maximum launches per site per year | launches/year |
|  | Payload per rocket launch | metric tons/launch |
|  | Annual capacity per elevator port, 179,000 | metric tons/year |
|  | Cost per metric ton for rocket transport | USD/metric ton |
|  | Cost per metric ton for space elevator transport | USD/metric ton |
|  | Total project timeline | Year |
|  | Total project cost | USD |
|  | Quantified environmental cost | N/A |

# Multi-Objective Optimization Model for Earth-Moon Logistics

## Model Formulation

### Problem Definition and Variable Setting

We address the Earth-Moon transportation optimization as a multi-objective linear programming problem with NP-hard complexity. The model focuses on optimizing the allocation of transportation resources between rockets and space elevators over a multi-decade timeline.

### Multi- Objective Optimization Framework

The model aims to minimize two core objectives: total cost () and total timeline (​). A weighted summation method is used for normalization (to eliminate unit differences), with weights ​,​ (​+​=1, adjustable based on policy priorities).

参考已有文献[]数据，我们假设在2050年后火箭年最大发射次数为8000次。

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|  |
| Fig. Rocket Launch Times Prediction Curve |

**Total Cost**

Total cost includes cumulative rocket launch costs and elevator operational costs over the project period:

|  |  |
| --- | --- |
|  | () |

**Total Timeline**

Total timeline is the weighted sum of years using the completion indicator (only the year of completion contributes to the timeline):

|  |  |
| --- | --- |
|  | () |

**Normalized Dual-Objective Function**

|  |  |
| --- | --- |
|  | () |

Where ​ is the normalized constant for cost (e.g., maximum possible cost if all materials use rockets), and ​ is the normalized constant for timeline (e.g., ​).

### Constraint Conditions:

All constraints are summarized below to ensure the model complies with material demand and capacity limits:

|  |  |
| --- | --- |
|  | () |

### NSGA-II Algorithm Implementation

Given the NP-hard nature of the problem and the requirement for multi-objective optimization, we employ the Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II). For chromosome encoding, a hybrid coding strategy is adopted: real-number encoding is used to represent the space elevator transport volume , integer encoding for the number of rocket launches , and binary encoding for the project completion status .Genetic operations include tournament selection, segment-based crossover, and Gaussian mutation (following an N(0,σ²) distribution), with safeguards to ensure non-negative costs after mutation. An elitist preservation strategy is implemented to retain the optimal solutions within the population. Constraint handling is achieved via an adaptive penalty function method based on violation severity, thereby guaranteeing the feasibility of the solutions.

## The Solution of Model 1

Based on the parameter settings provided in Section 4.2, we conducted numerical simulations to solve the spatiotemporal network flow model. The key parameters are set as follows:

### Scenario a: Pure Space Elevator System

In this scenario, all materials are transported via the space elevators of the three Galactic Harbours. The annual lifting capacity per Galactic Harbour is ***metric tons/year***.

Although the pure space elevator scenario (***,* 1.0×1013 *USD***) boasts the lowest cost and zero atmospheric emissions, its extended timeline makes it less suitable for this project.

### Scenario b: Pure Rocket Launch System

This scenario relies solely on the 10 global rocket launch sites. Given the maximum launch rate of 800 per site per year and a payload capacity of 150 tons per launch, the total annual delivery capacity is **1,200,000**.

The exclusive use of rockets results in a prohibitive timeline exceeding ***years*** and an astronomical cost of approximately **5.0×**. This clearly demonstrates the infeasibility of relying solely on current rocket technology for large-scale lunar colonization logistics.

### Scenario c: Hybrid Transportation System (Optimized Solution)

为在成本与时间目标之间实现最优权衡，本研究构建了基于 NSGA-II 算法的多目标优化模型。算法参数设定如下：种群规模100、迭代次数700 代、交叉概率0.7、变异概率0.2，采用锦标赛选择与自适应罚函数法处理约束。在成本与时间权重1:1的设定下，通过迭代求解得到帕累托最优解集，其关键参数如下：

**优化结果参数显示**，混合运输系统的最早完成年份为：

|  |  |
| --- | --- |
| 164 years |  |

In terms of material allocation, the transport volume distribution is determined as:

|  |  |
| --- | --- |
|  |  |

优化后总成本：

|  |  |
| --- | --- |
| 2.381× *USD* |  |

The optimized hybrid solution represents the **Pareto-optimal solution**​ for the equal weighting of cost and time, adopting a capacity allocation scheme where rockets undertake **34.52%** of the transport volume and space elevators assume **65.48%**. This result verifies the space elevator’s economic superiority as the backbone of large-scale Earth-Moon logistics, with rockets supplementing critical and specialized cargo. The solution outperforms standalone systems in balancing timeline and cost, underscores the hybrid architecture’s advantages, and provides a scientifically feasible optimization pathway for lunar base logistics.

### 算法收敛性与结果可视化

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| Fig. Evolution of Cost and Timeline During NSGA-II Iteration |

This figure illustrates the dynamic convergence characteristics of the optimal and average values of total cost and project timeline with the iteration process after 1000 generations of the NSGA-II algorithm, intuitively verifying the stability and effectiveness of the algorithm in solving the multi-objective optimization problem of Earth-Moon logistics.

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|  |
| Fig. Evolution of Pareto Front Across Different Iteration Stages |

This figure presents the evolutionary process of the Pareto front from the initial iteration to the final generation (Gen999), including gradual compaction, homogenization, and convergence towards the ideal optimal region, reflecting the algorithm’s efficient exploration capability of the solution space and the screening effect of high-quality non-dominated solutions.

|  |
| --- |
|  |
| Fig. 3 Final Generation Population Distribution and Fitness Evolution |

teristics of the Gen999 population in the two-dimensional cost-timeline space and the marked raw optimal individual, while the right part presents the stable evolutionary trend of fitness during the iteration process, laying a solid foundation for deriving the constrained optimized solution that meets the total material demand.

|  |
| --- |
|  |
| Fig. The Distribution Characteristics of Pareto Optimal Solutions |

第一问的帕累托最优解分布如图 2-1 所示：前沿面呈现 “成本上升时工期下降” 的权衡关系，峰值区域对应 “成本 - 工期” 的最优平衡区间，为后续方案选择提供了多目标优化依据。

# Non-Ideal Operating Conditions Resilience Assessment Model

## Model Establishment

### Weibull Distribution + Nonlinear Dynamics Integrated Modeling Principle

This spatiotemporal stochastic network flow model assesses the resilience of the Earth-Moon transportation system under non-ideal conditions. It uses the Weibull distribution to model space elevator failure probability and characterize random equipment failures, and literature-derived high-dimensional nonlinear dynamics to simulate tether oscillation and its nonlinear chaotic characteristics. Integrated with the two core modules, Monte Carlo simulation generates time-series failure samples, which are input into a heuristic optimization module for adaptive spatiotemporal capacity allocation to realize rational fault-state resource scheduling. This method balances scenario characterization accuracy and computational efficiency, providing a reliable tool for the system's resilience assessment.

## Mathematical Formulation

### Weibull Distribution-Based Failure Probability Modeling

Since space elevators currently only exist in theoretical concepts, the Weibull distribution is selected to characterize the randomness of their failures over time:

|  |  |
| --- | --- |
|  | () |

where ​ (scale parameter) and ​ (shape parameter) are typically estimated by expert experience or historical data. For simplified calculation, we assume the annual failure probability of the space elevator is 5‰ with a single maintenance duration of 2 months, resulting in an annual available time ratio =0.8**‰**.

### Emergency Risk Quantification via Statistical Analysis

For unforeseen emergencies in the Apex-Moon segment, based on engineering experience and space mission risk analysis, this study assumes an emergency occurrence probability of 1% with a corresponding 30% capacity loss, and defines the comprehensive capacity loss coefficient under this scenario as =3‰.

### Rocket Launch Success Probability Based on Empirical Data

The rocket launch success probability is a key parameter for calculating the effective delivery volume. Taking the Cape Canaveral/KSC launch site as a reference and based on open data [], the launch success probability is assumed to be PR=98% and subject to the binomial distribution.

### Total Transport Capacity Guarantee Under Chance Constraints

Incorporating the impact coefficients of faults and oscillations, the actual delivery volume is calculated in two parts as follows:

Space elevator delivery volume:

|  |  |
| --- | --- |
|  | () |

Where ​=125denotes the annual baseline transport capacity of a single space elevator port, determined by truncating the normal distribution N( =125, =) to the interval [100, 150]i.e.,=125.

Rocket delivery volume:

|  |  |
| --- | --- |
|  | () |

### Total Transport Capacity Assurance Under Chance Constraints

the chance constraint for the stochastic spatiotemporal network flow is formulated as follows:

|  |  |
| --- | --- |
| *P* ()*≥1−ε* | () |

Where ε denotes the allowable violation probability, set to 5% with reference to general engineering risk management criteria.

### Construction of Resilience Evaluation Index System

To comprehensively evaluate system resilience, three categories of core indicators are defined to reflect the impacts of non-ideal operating conditions:

Time increment  quantifies transportation delays caused by non-ideal operating conditions.

Cost increment measures the additional costs arising from faults and subsequent adjustments.

Transport capacity structure change：Characterizes the adjustment range of the volume share between space elevator and rocket transportation, reflecting the adaptability of resource allocation.

## 适配策略设计

### 冗余运力替代策略

The 10% capacity replacement principle is a heuristic parameter derived from engineering empirical values, system redundancy and cost optimization strategies. To compensate for the capacity loss caused by space elevator faults, rocket transportation is adopted for supplementary delivery, with a unit replacement cost：.

### Dynamic Capacity Allocation Based on Real-Time Status

根据系统实时运行状态，调整太空电梯与火箭的运输任务比例。当某一运输模式受非理想工况影响时，适当提高另一模式的任务占比，保障系统整体运输效率。

上述适配策略可通过调整运力分配与维护时机，缓解非理想工况对系统的冲击，其效果将通过以下量化结果验证。

## 模型结果

基于蒙特卡洛模拟生成的1000个随机故障场景，经数据压缩与均值计算，非理想工况下地月运输系统的核心性能指标如下：总工期为169年，总成本为4.714× 美元，火箭运输量为54954000吨，太空电梯运输量为45045315吨，二者运力占比分别为54.95%与45.05%。

结合第一问理想工况的帕累托最优解，通过韧性评估指标量化非理想工况的影响：时间增量ΔT=5年，延误率约3.04%；成本增量=2.333×美元，增幅达97.9%。

Under ideal operating conditions, the space elevator system dominates the logistics network due to its significantly lower unit cost and stable continuous capacity, resulting in an optimal allocation of approximately 65% elevator transport and 35% rocket transport.

However, once non-ideal operational factors are introduced—such as tether oscillations, system failures, maintenance downtime, and stochastic capacity reductions—the role of the space elevator fundamentally changes. Although its expected annual capacity remains high, the increased variance in available capacity introduces substantial schedule risk under a hard delivery deadline.

In contrast, traditional rockets, despite higher unit costs, provide highly reliable, modular, and rapidly recoverable transport capacity. As a result, the optimization shifts toward a risk-hedged strategy, increasing rocket utilization to 55% in order to maintain delivery reliability and satisfy probabilistic completion constraints.

This transition reflects not a failure of the space elevator concept, but a rational rebalancing of cost efficiency and system resilience in a stochastic logistics environment.

**非理想工况下系统核心指标的分布特征与运力结构稳定性可通过统计图表进一步阐释与验证：**

|  |
| --- |
|  |
| Fig. Bar Chart of Core Indicators Comparison Under Non-Ideal Conditions |

该图两组柱状数据对比，直观呈现非理想工况下系统核心指标的量化结果，明确其与理想工况的偏差范围。

|  |
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| Fig. 2 Scatter Plot of Capacity Structure Ratio Under Non-Ideal Conditions |

该图通过散点分布直观反映运力占比的离散特征，验证非理想工况下系统运力结构具备良好的稳定性与抗扰动能力。

|  |
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| Fig. 2 Comparative Probability Density Distributions of Time and Cost |

此图通过并排核密度估计（KDE）曲线对比两个关键变量的分布。

# 月球基地水资源持续补给规划

## 模型建立

针对10万人月球基地水资源持续补给的需求，本研究构建融合自回归与滑动平均的ARMA(1,7)时域模型。模型以天为时间单位，模拟一年周期内水资源的动态变化，旨在精确计算维持水系统稳态所需的额外运输成本，评估地月混合运输系统对该常态化补给任务的适配性。

水资源系统的基本动力学描述基于存量平衡原理，存量随时间的变化源于补给、消耗与回收的动态平衡，微分表达为：

|  |  |
| --- | --- |
|  | () |

假设基地采用高效的水处理与循环系统，设定水回收效率 =0.98。该参数参考 NASA 再生环境控制与生命支持系统技术目标，Ellery（2021）研究指出月球任务水闭合度需显著高于国际空间站当前93% 水平，98% 设定符合探索任务高资源循环率要求。将此关系代入并以一天为步长离散化，得到基础差分方程：

|  |  |
| --- | --- |
|  | () |

不难发现满足 AR（1）模型的形式，然而将和视为简单常数显然不符合复杂的现实情况、鲁棒性太弱，因此我们引入 MA 模型，将其分解为平均项与波动项，以精准刻画用水波动、运输不确定性及库存反馈调节的动态特性。

10 万人基地日均总用水量设定为30,000吨，对应人均日用水量 300 升[NASA Human Factors Technical Briefing, 2024]取值位于典型城市综合用水量 250-350 升/人/天，涵盖科研、生活及潜在损耗。每日实际用水量 ，随机波动 ，周末用水量较工作日降低20%。稳态补给需求吨/天，每日实际总补给量 ，其中为基于库存反馈的动态调节指令，为运输不确定性。

模型嵌入现实运输约束，补给指令存在平均*d*=7天的运输延迟，参考地月运输任务的典型周期。系统根据当前库存水平与目标安全库存吨（约1.7天的用水缓冲）的偏差，通过反馈函数动态调节补给指令：

|  |  |
| --- | --- |
| *=**β ⋅* (*+*)*⋅* | () |

反馈函数定义为：

|  |  |
| --- | --- |
|  | () |

系统根据库存偏差调节补给强度的逻辑为：库存过高时停止补给避免存储成本浪费，库存正常时按0.5倍强度补给，库存偏低时按1.0倍强度补给，库存严重不足时按1.5 倍强度紧急补给，保障基地用水安全。

综合所有机制，完整 ARMA (1,7) 模型表达式为：

|  |  |
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其中，为资源抢占系数，取值0.8，表征水补给任务对运输通道的占用程度。水资源补给关乎人员生命安全，需优先占用 80% 运输通道，降低与建设物资的竞争风险，该取值参考 NASA 探索任务生命支持物资优先运输准则。为 t-1 时刻的补给指令波动，权重满足。

模型中自相关函数（ACF）基于协方差计算，偏自相关函数（PACF）通过Yule-Walker 方程求解，确保模型平稳性与拟合效果。运输成本核算沿用混合运输权重，火箭运输承担35%，太空电梯承担65%，符合近中期地月物流系统的预期构成。

## 模型求解与结果分析

### 求解方法

基于 ARMA (1,7) 模型，以 365 天为模拟周期，求解流程如下：

通过生成含周末20%衰减的用水波动序列和运输不确定性序列(0,)，迭代计算得到水资源管理系统的全年运行轨迹；通过Yule-Walker方程计算PACF、基于协方差计算 ACF，验证模型平稳性；代入基础参数与反馈函数，逐天迭代计算水库存量与每日补给量;按火箭35%、太空电梯65%的概率权重分配每日补给量；结合单位运输成本，汇总全年额外运输成本。

|  |
| --- |
|  |
| Fig. 1 Storage Variation & Supply Delay in a Year |

### 核心结果量化

模型求解结果显示，年尺度补给总量占年总用水量的比例为：

|  |  |
| --- | --- |
|  |  |
|  | | | |
| Fig. 3 Csdstributionsdd and Cost | | | |

每日补给量满足动态分解关系：稳态部分 占比约 90%，指令波动​与运输不确定性​合计占比约10%，符合常态化补给的动态变化规律。

每日补给的运输方式分配可通过调度时间表（图 6-1）直观体现：

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|  |
| Fig. 2 Comparative Probability Density Distributions of Time and Cost |

火箭承担32.9% 的补给天数，主要覆盖库存偏低时的应急补给；电梯承担67.1% 的补给天数，主要负责常态化稳态补给。表中条形长度对应每日补给量，进一步印证 “库存低时补给量增加” 的反馈调节逻辑。

全年额外运输需求为：

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| --- | --- |
|  |  |

全年补给总成本为：

|  |
| --- |
| *=*8.45 ×*USD* |

成本结构分析显示为：

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| --- | --- |
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### 结果意义阐释

AR系数接近1，表明系统库存仅存在轻微衰减，惯性极强；补给占比与理论净损耗率的一致性，印证模型参数设定与机制设计的科学性。每日补给量的动态分解，体现模型对现实随机性的精准刻画，指令波动与运输不确定性的纳入提升了方案的实操性。

模型的动力学特性为观测结果提供解释：用水波动的影响被系数(1−*η*)=0.02显著衰减：

该衰减效应避免短期用水波动引发库存剧烈波动，进一步印证模型的稳定性设计。

运输延迟效应通过滑动平均项体现：.其中，为 t-1 时刻的补给指令波动，近期运输延迟对当前库存的影响权重更高。

成本计算结果反映混合运输模式的经济性：太空电梯凭借低成本优势降低长期补给负担，火箭则通过高优先级保障紧急需求，二者结合既满足成本控制目标，又保障补给可靠性，为月球基地水资源常态化补给提供科学可行的方案支撑。模型结果可为地月运输系统的常态化补给调度提供量化依据，后续可结合原位水资源利用技术，进一步降低地球补给依赖。

1. **Optimization of Environmental Impacts of Transportation Systems**

**7.1 Model Framework and Quantitative Methodology**

To achieve the synergistic optimization of the economy and environment for the cislunar transportation system, this study constructs a comprehensive model framework integrated with generalized cost analysis. The core innovation of this framework lies in the monetization of abstract environmental impacts, which provides a quantitative basis for decision-making in the context of carbon allowances in.

### Core Decision-Making Mechanism: Generalized Cost Function

By introducing the carbon shadow price, the model internalizes environmental externalities and establishes the core decision-making function:

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The Entropy Weight Method is adopted for the objective allocation of weights to each environmental indicator, which avoids subjective biases and ensures the scientificity and neutrality of the model results.

***shangquanfa***

### Quantification of Multi-dimensional Environmental Impacts

The model breaks through the limitation of a single carbon emission indicator, proposes four key environmental impact parameters, and accurately depicts the unique environmental impacts of rocket launches:

**Ozone Layer Depletion:**

Focusing on the amplification effect of stratospheric injection. denotes the stratospheric amplification factor (solid rockets > liquid rockets), which enables us to effectively distinguish the differences between technical pathways.

**Climate Warming:**

Repeated rocket launches emit a large amount of black carbon into the stratosphere, which has become a non-negligible factor contributing to the greenhouse effect.

**Aerosol Disturbance:**

Quantifying the disturbances to cloud formation and radiation.

**Cumulative Greenhouse Gas Emissions:** The comprehensive emissions throughout the entire life cycle of transportation are accounted for and quantified by the total volume method.

### Environmental Impact Target Function

Based on the aforementioned parameters, the model establishes the environmental impact target function:

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Among them,and denote the unit environmental costs accurately quantified by sub-models..

The model integrates multi-dimensional environmental impacts into a unified target function to realize comprehensive optimization:

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| --- | --- |
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Among them, denotes the reference benchmark value for each objective, and the weight wi​ can be set via the Entropy Weight Method or policy preferences.

### Comprehensive Environmental Impact Judgment Function and Critical Mechanism

The model innovatively defines the comprehensive environmental impact judgment function:

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When , we consider the environmental impact during the operational phase to be negligible.Among them,denotes the system's effective emission power, andis the solar constant, which together form a relative scale for energy input. represents the total spatial occupation area of the mission chain, and is the biosphere carrying capacity of the reference area, which is used to evaluate the ecological pressure of spatial occupation. quantifies the deviation degree of the additional radiation flux induced by human activities from the natural background value , and is normalized by the natural standard deviation of environmental disturbance.

### Scenario Setting and System Constraints

To ensure the credibility of simulation results, practical constraint conditions have been incorporated into the model:

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Among them, denotes the critical annual launch frequency. is the annual upper limit of acceptable environmental impacts derived by back-solving the condition . represents the mass of specific substances emitted per single launch, and are the environmental impact amplification factors or residence times of the corresponding substances in the stratosphere.

## Multi-scenario Simulation and Analysis of Optimization Strategies

### Comparison of Environmental Impacts and Multi-objective Values Across Three Types of Transportation Scenarios

Based on the multi-objective optimization solution of the genetic algorithm (NSGA), combined with constraints including a maximum annual rocket launch frequency of 8000, an annual transportation capacity of 537,000 tons for the space elevator, and a launch success rate of 98.5%, the environmental impacts and multi-objective optimization paths for the three types of scenarios are as follows:

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| Fig.1 ZE Impact Surface Optimization |
| The Pareto frontier solutions of the final generation show that the optimal value of is achieved when the proportion of rocket transportation reaches 32.9% and that of space elevator transportation stands at 67.1%. At this point, the cost is ×USD, the time consumption is  years, and the shadow price of environmental cost is .The generalized cost is .In addition, the final results indicate that the average annual launch frequency ,which is consistent with the expected results.  **结果阐释ai生成** |
|  |
|  |
| Fig. 2 Transportation Distribution & Timetable |

# Sensitivity Analysis

# Model Evaluation and Further Discussion

## Strengths

## Weaknesses

Relevant studies have shown that space elevators are only suitable for transporting small-scale cargo, and certain construction materials can only be delivered to the lunar base by rockets, a transportation constraint not incorporated in the **modeling analysis of Problem 1**.

## Further Discussion

进行进一步的讨论，这里可以写模型的改进和拓展：虽已，与理论上限，NP陡峭最优解，灵活的在启发式和

模型的改进：主要是针对模型中缺点有哪些可以改进的地方；

模型的拓展：将原题的要求进行扩展，进一步讨论模型的实用性和可行性。

# Conclusion

结论部分，这个部分在国赛论文很少见到，但在美赛中出现的频率很高。

这个部分可以是论文中心思想的重申、研究结果或主要观点的归纳，也可以是某些启示性的解释或考虑。

有些论文把“Model Evaluation and Further Discussion”的内容放到了结论部分，这也是可以的，大家可以灵活调整。

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# Appendices

|  |
| --- |
| Appendix 1 |
| Introduce: 这里放上附录1的介绍 |
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| --- |
| Appendix 2 |
| Introduce: 这里放上附录2的介绍 |
|  |

本部分是附录部分，美赛对于附录不是特别看重，今年还限制了论文的页数（从第二页开始编号，不能超过25页）。

一般新起一页列出附录。

在不超过页数限制的条件下，附录中可以包括下面内容：

* 你们写的代码；
* 某一问题的详细证明或求解过程；
* 自己在网上找到的数据；
* 比较大的流程图；
* 较繁杂的图表或计算结果。