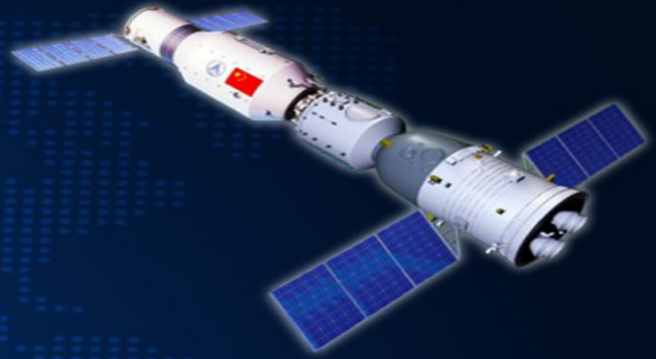
——GTOC 12 Workshop, Jan 15, 2024



# Methods and Results from Team NUDT-LIPSAM


**Jiacheng Zhang, Hanwei Wang, Ke Jin, Yu Zhang, Lifeng Fu, Sai Zhang, Miao Feng, Yuehe Zhu**

College of Aerospace Science and Engineering
National University of Defense Technology, China

# 目 录

CONTENTS

## Problem Characteristics

- This is a multi-spacecraft multi-target selective rendezvous sequence planning problem with a novel challenge of collaborative revisit.
- The second-stage combinatorial problem is defined by the first-stage selection problem.
- The trade-off between body-to-body transfer time and fuel cost is important. Longer transfer durations lead to lower transfer cost and more accessible asteroids, but short mining time.

**Low-thrust trajectory optimization**

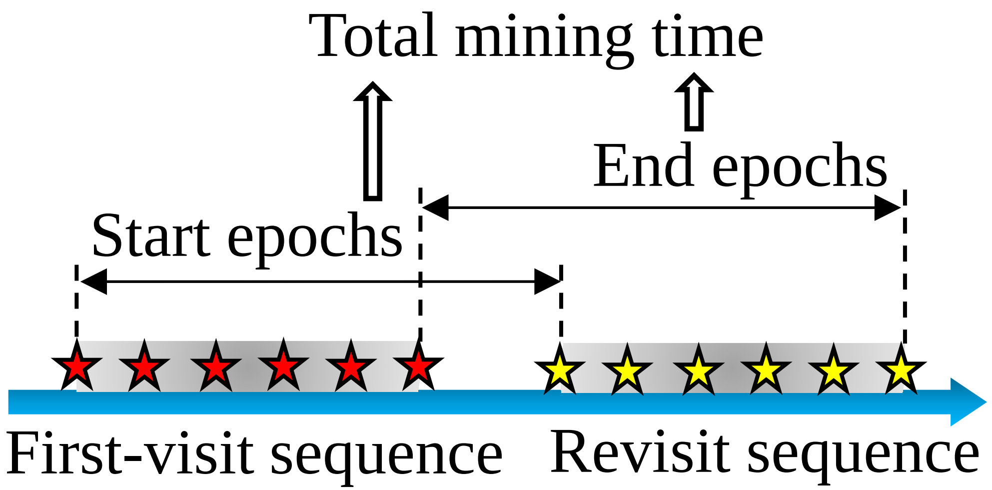
Transfer time ⟷ Trade-off ⟷ Fuel cost

**Combinatorial optimization for revisit rendezvous sequence**

Target selection and first visit → Collaborative revisit

## Objective Function

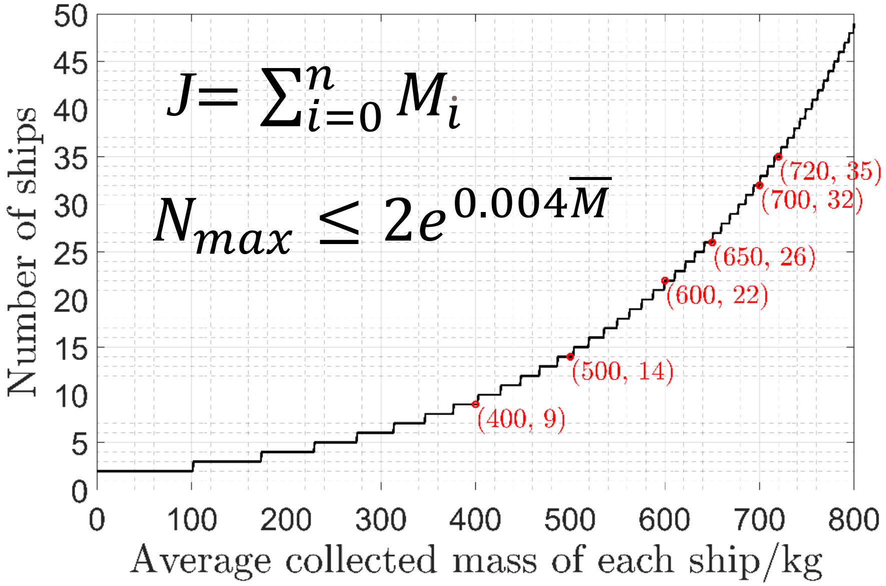
- The objective function is mainly determined by the visiting time interval of each mined asteroid and the total number of all mined asteroids.
- It can be simplified to make the end epoch of the first-visit sequence as early as possible, and the start epoch of the revisit sequence as late as possible.
- If wants to use more ships, the average mined mass must be improved.




**Timeline of one ship**

$$J = \sum_{i=0}^{n} M_i$$

$$N_{max} \le 2e^{0.004\overline{M}}$$




| $\overline{M}$(kg) | $N_{max}$ | $\overline{M}$(kg) | $N_{max}$ |
|---|---|---|---|
| 400 | 9 | 660 | 28 |
| 500 | 14 | 669 | 29 |
| 600 | 22 | 678 | 30 |
| 611 | 23 | 686 | 31 |
| 622 | 24 | 694 | 32 |
| 632 | 25 | 702 | 33 |
| 642 | 26 | 709 | 34 |
| 651 | 27 | 716 | 35 |


目 录
CONTENTS

## 0 Solving framework

- **Preparation**: ① Pre-screen promising asteroids, ② Find all optimal transfers to the first (last) target, and ③ Pre-train a DNN-based estimator for optimal transfer costs.
- **Problem Decomposition**: ① Search promising first-visit sequences, ② Optimize revisit sequence by sampling first-visit ones, ③ Further improve the rendezvous epochs

### I. Preliminary works

**Step 1: Candidate asteroids subset with** $e < 0.05$, $i < 5°$, **and** $\Delta a < 0.1$ AU

↓

**Step 2: Database of all earliest earth-departure and latest earth-arrival optimal transfers**

↓

**Step 3: Neural network to estimate the optimal body-to-body transfer fuel cost**

### II. Global optimization

**Step 1: Database of first-visit sequences with** $n$>7, $T_f$ **<** 2000 days **and** $m_{p,rest}$ > 1100kg

↓

**Step 2: For a first-visit sequence, use the same ship to revisit them and count the collected mass**

↓

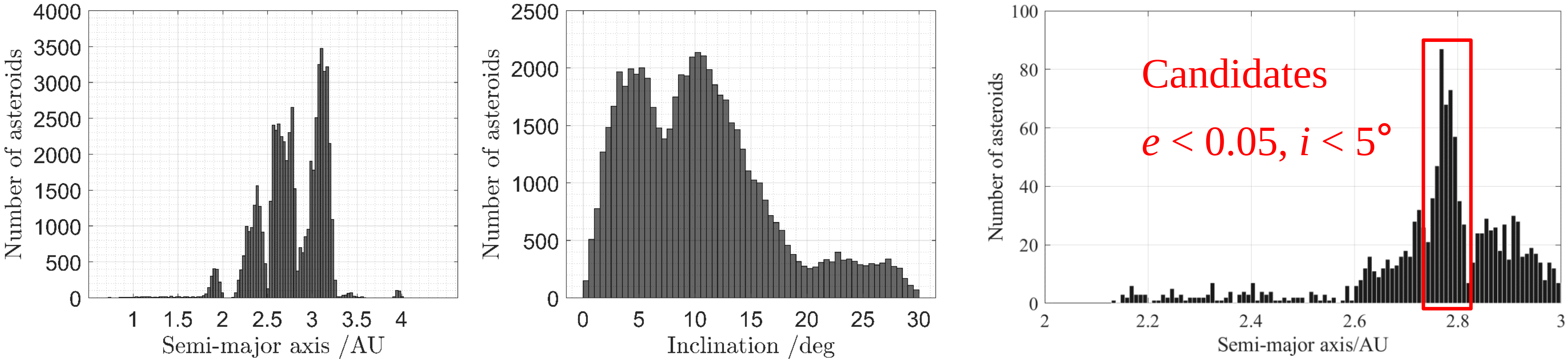
**Step 3: Further optimize the rendezvous epochs of each complete sequence**

## 1 Candidate Asteroid Selection

- A subset of asteroids with small eccentricity and inclination is preferred for successive low-thrust rendezvous in a long term.
- The asteroids with **eccentricity less than 0.05 and inclination less than 5 degree** are mainly distributed in **2.76~2.80AU**.
- The concentrated semi-major axis can make the longitude not disperse over a long term.

**Orbit Distribution of All Candidate Asteroids**

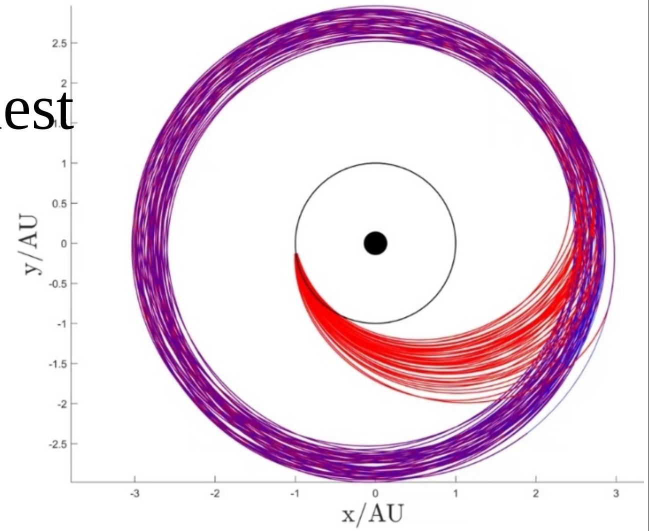
**Asteroids with *e* < 0.05, *i* < 5 deg**



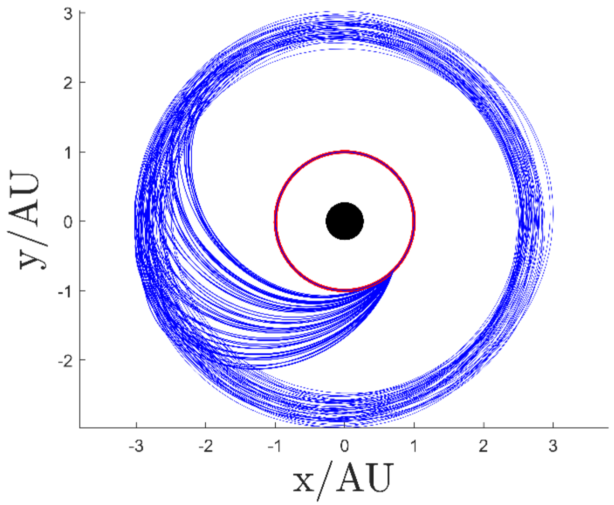
## 2 Database of the earth-departure and the earth-arrival transfers

- The earliest earth-departure and latest earth-arrival transfers for all candidates are computed.
- It is a low-thrust flyby trajectory optimization problem with limited boundary Δ*v*.
- In order to make the arrival time at the first asteroid as early as possible, and the departure time from the last asteroid as late as possible, we did not use the gravity assistance.

Database of all earliest Earth-departure transfers for all selected candidates.

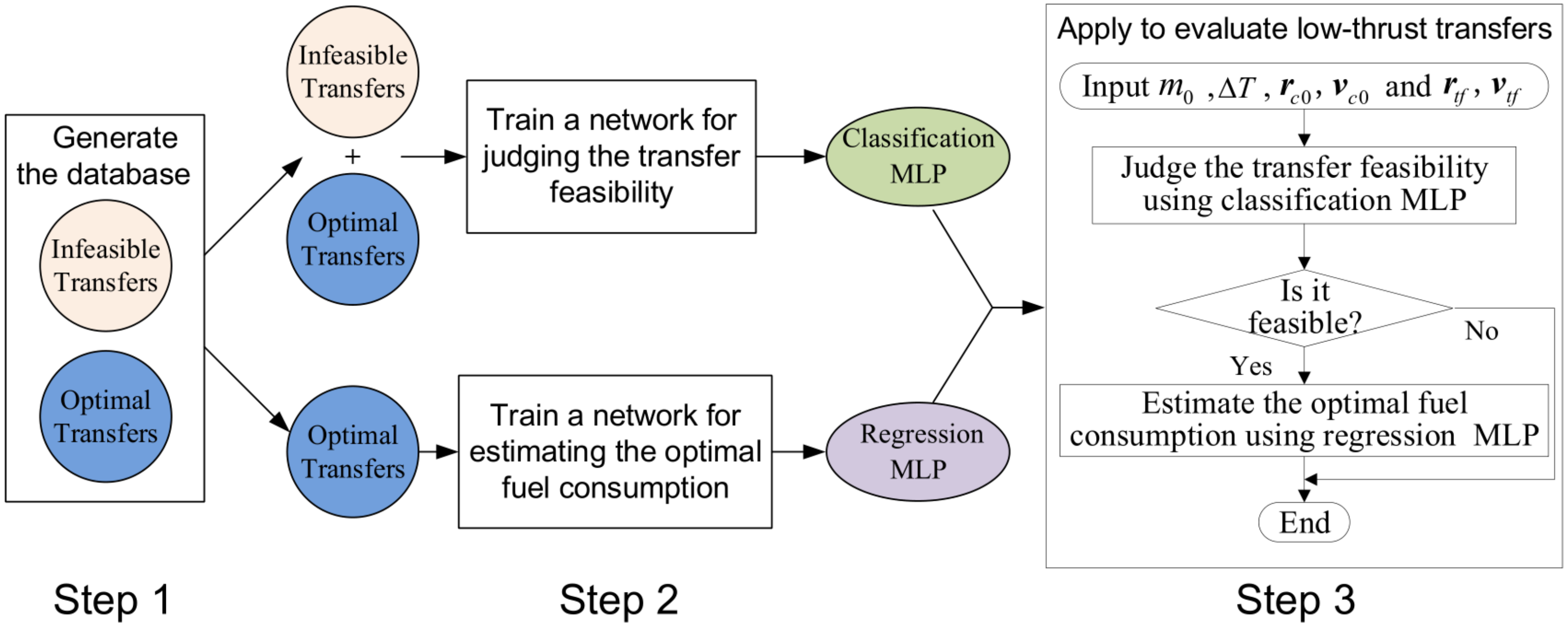



Database of all latest Earth-arrival transfers for all selected candidates.



## 3 ML-based method to quickly evaluate the body-to-body transfer

- Generate millions of transfer samples (infeasible and optimal transfers)
- Train two networks (judge the transfer feasibility and estimate the optimal fuel cost)
- Evaluate a transfer with any condition using proper learning features (orbit Elements, relative position and velocity, $\Delta T$ and Lambert $\Delta v$)




**Accuracy of judging the transfer feasibility:**
**98%**

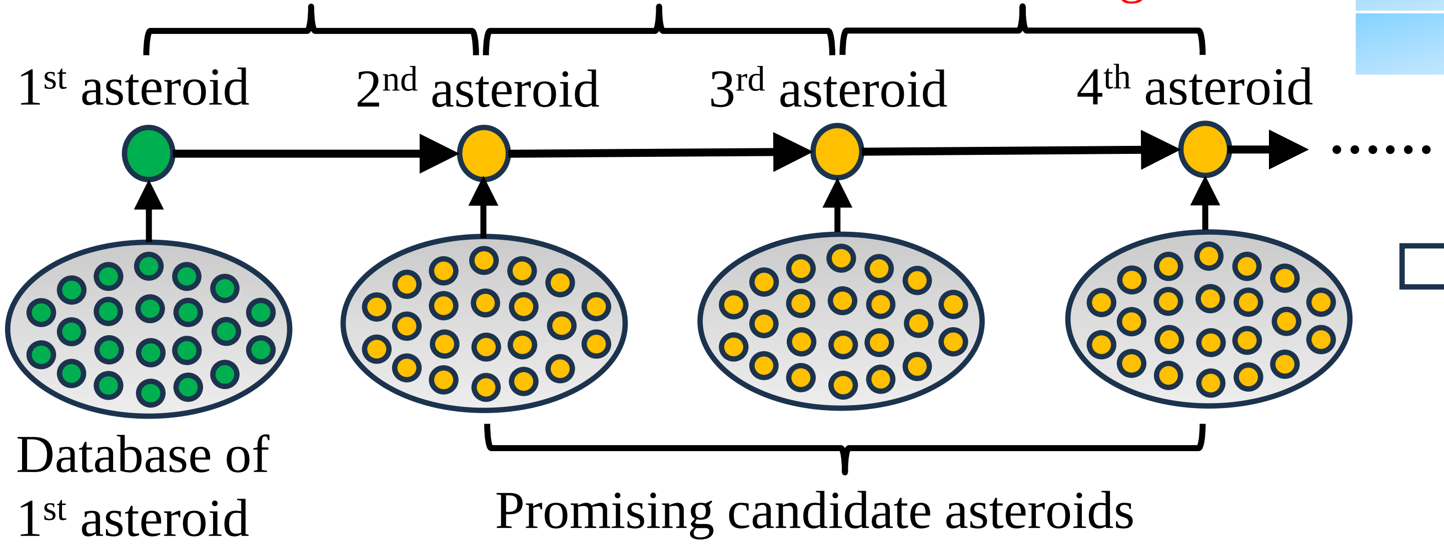
**Error of estimating the optimal fuel cost:**
**0.4%**

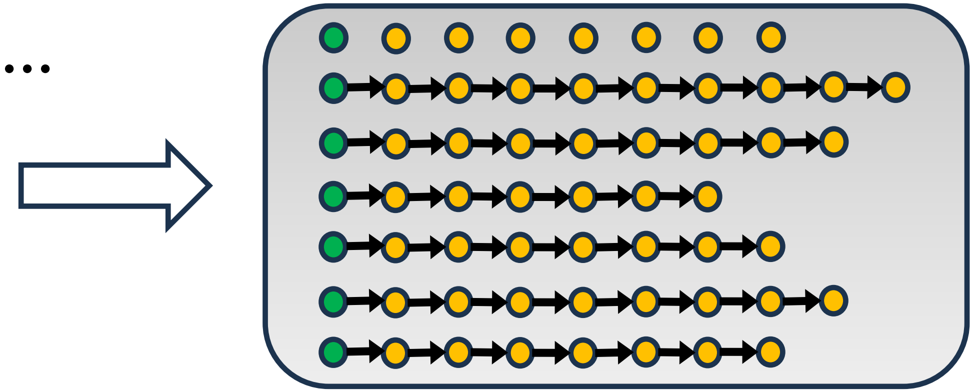
## 4 Stochastic heuristic to search the first-visit sequences

- A stochastic heuristic is proposed to build a database of the first-visit sequence.
- The targets are selected one after another with some limitations to construct a sequence.
- After each selection, the transfer duration and fuel cost are generated by the network.

| $N_{as}$ | $N_{seq}$ | $\overline{M}_{fuel}$(kg) | $T_f$(day) |
|---|---|---|---|
| 8 | 5000 | 1100 | 1700 |
| 9 | 500 | 1100 | 1900 |
| 10 | 50 | 1000 | 2100 |

- The maximum distance is limited to within 2e6km.
- Transfer duration is limited in [80, 200] days.
- Transfer fuel cost is limited to less than 200 kg.

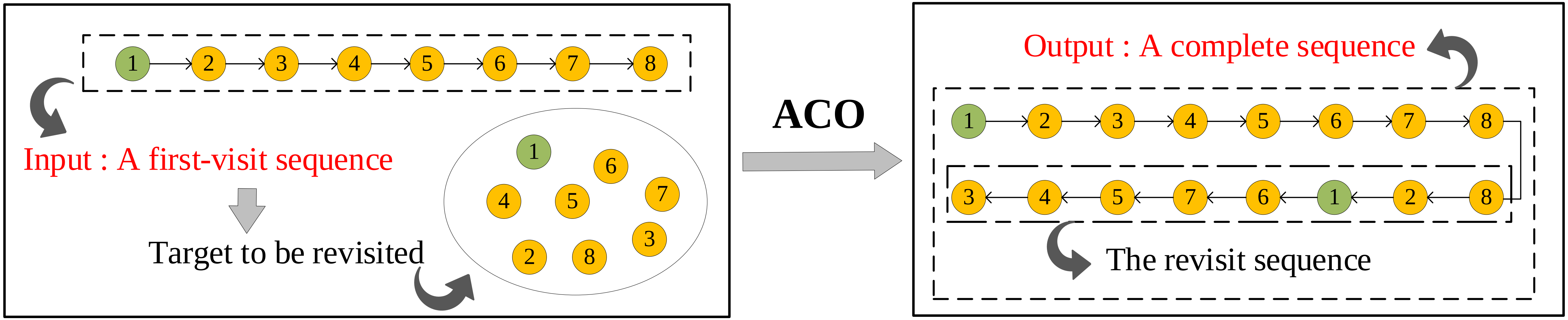


**Database of first-visit sequences**

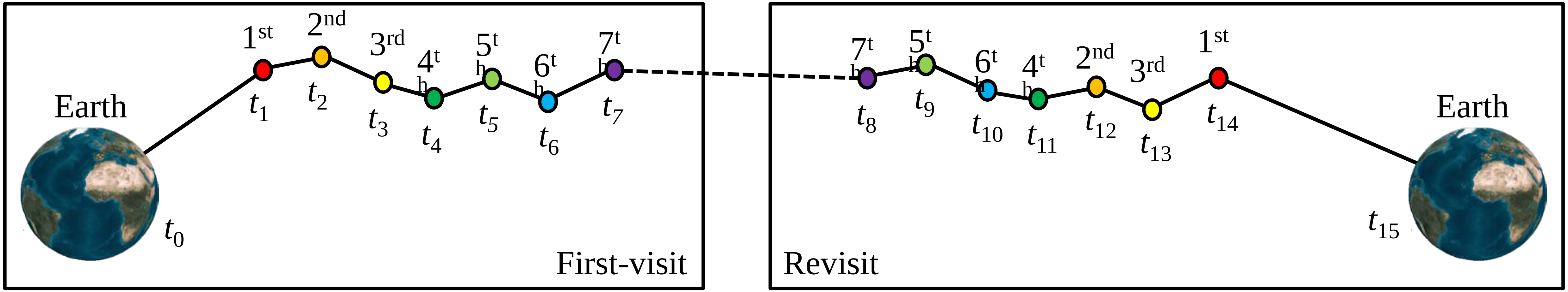
## 5 ACO for planning the revisit sequence

- On the basis of the first-visit sequence, ACO was used to optimize the revisit sequence.
- The revisit targets are the same as the first-visit asteroid for each mining ship.
- The mining ship will stay on the asteroid after setting up the last miner.



## 6 Re-optimize the rendezvous epochs and B2B transfers for a ship (sequence)

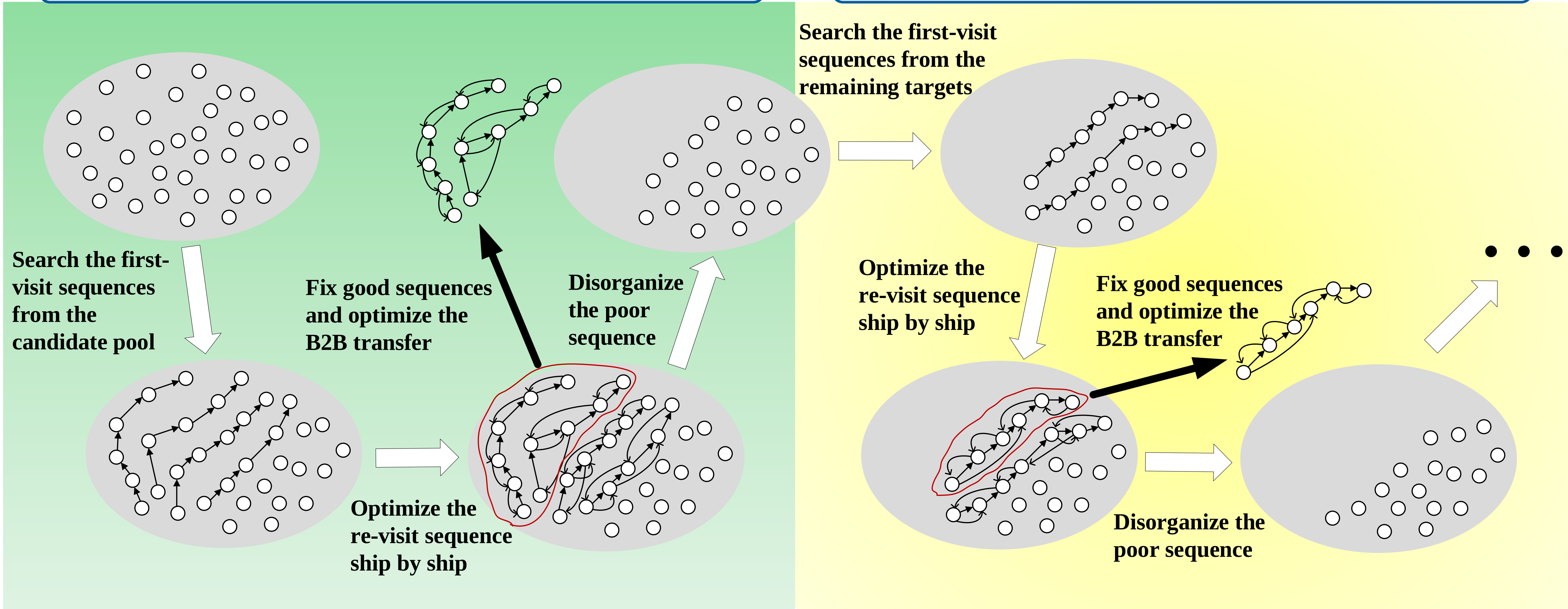
- The sequence is fixed and the Earth departure epoch, the asteroid rendezvous epochs, the Earth returning epoch, and the thrust epochs and directions of each transfer are reoptimized.
- It is a **nested optimization problem**, and the rendezvous epochs and all B2B transfers are simultaneously optimized using a DE and an indirect method.
- A little bit time-consuming (20 min for each ship) but can obtain a fully optimized sequence.



## 7 Construct a Solution and Update Sequences by Sequences

**Construct a solution of many sequences**

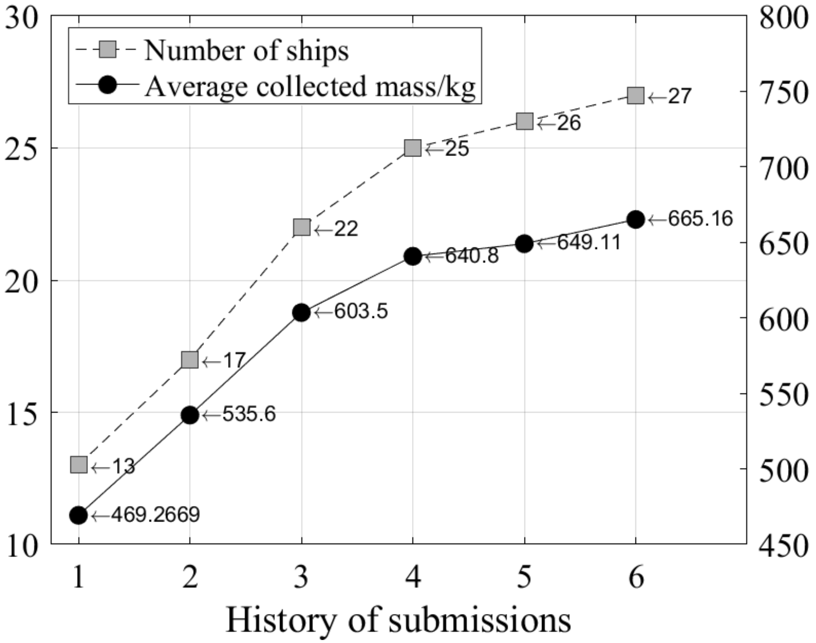
**Update sequences by sequences**



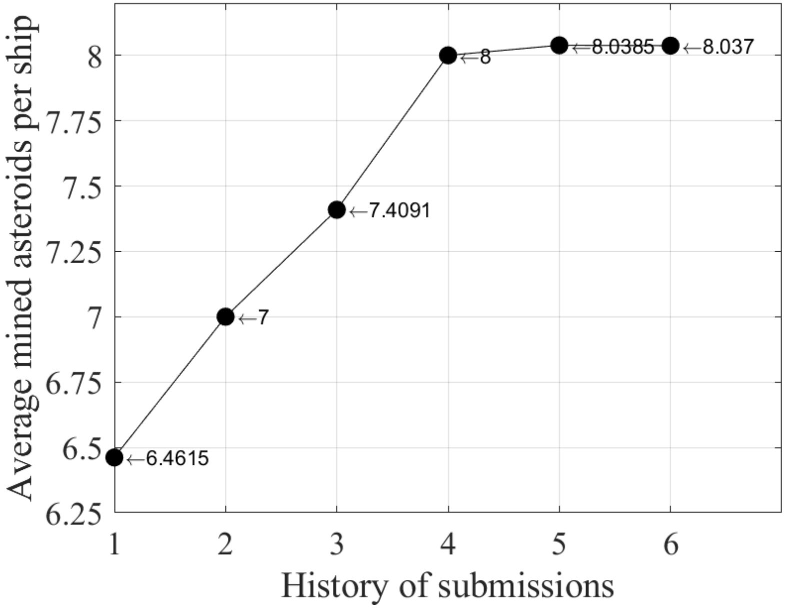
## 8 Results submitted at the end of the competition

At the end of the competition, we submitted a result with 27 ships, 217 asteroids, the average collected mass of 665 kg, and the total collected mass of 17591 kg

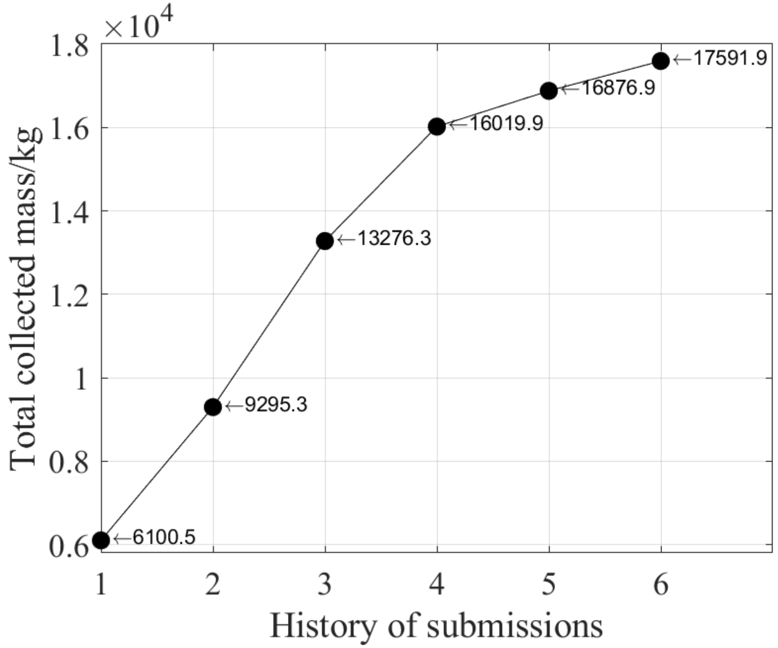
**Ship number and average collected mass**




**Average asteroid number**




**Total collected mass**



# 目 录

CONTENTS

# 1 Advantages and issues of the applied methods

## Advantages

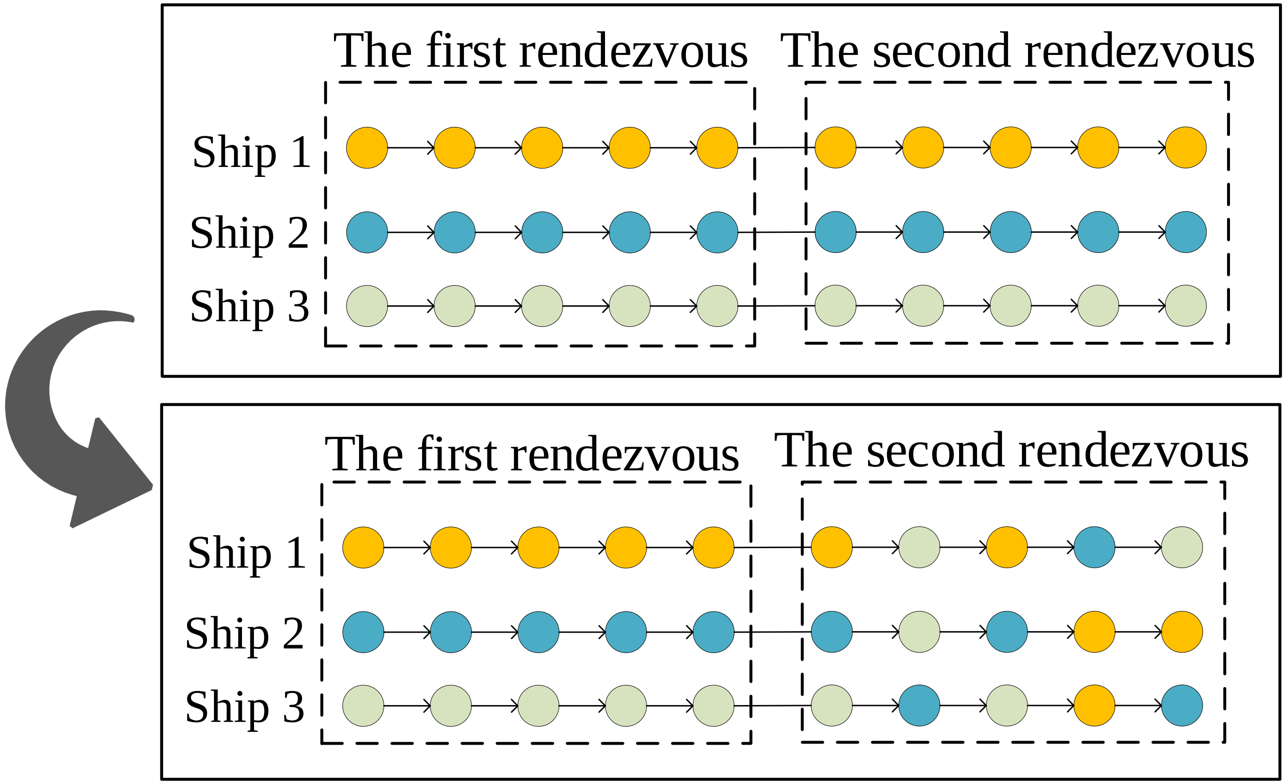
- Appropriate simplification and decomposition reduced the scale of the problem and the coupling degree between various subproblems.
- Our methods can quickly improve the overall solution by updating a single sequence one after another, without the optimization for all sequences.

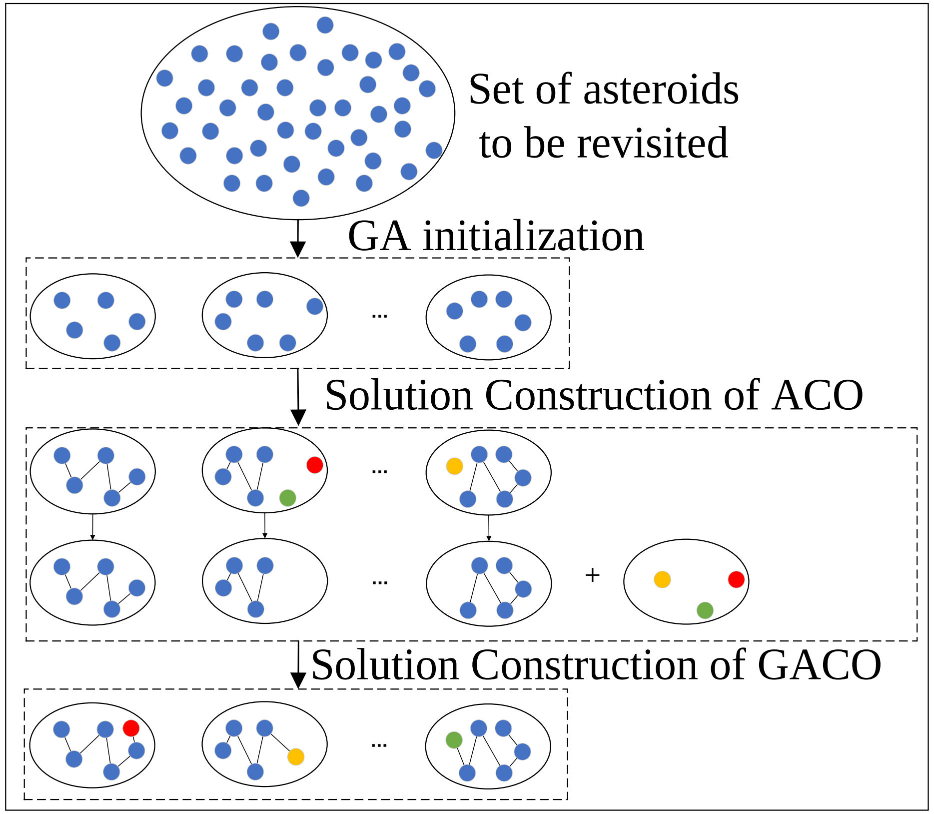
## Issues

- Optimize the rendezvous epochs and low-thrust transfer trajectories simultaneously is not efficient.
- Updating the overall solution sequences by sequences lacks globality and can only obtain locally optimal results.

## 2 Improvement

- Mining ships no longer works alone and complete the mining mission cooperatively.
- A hybrid evolutionary algorithm is designed for solving the cooperative re-visit of multiple mining ships to asteroids.

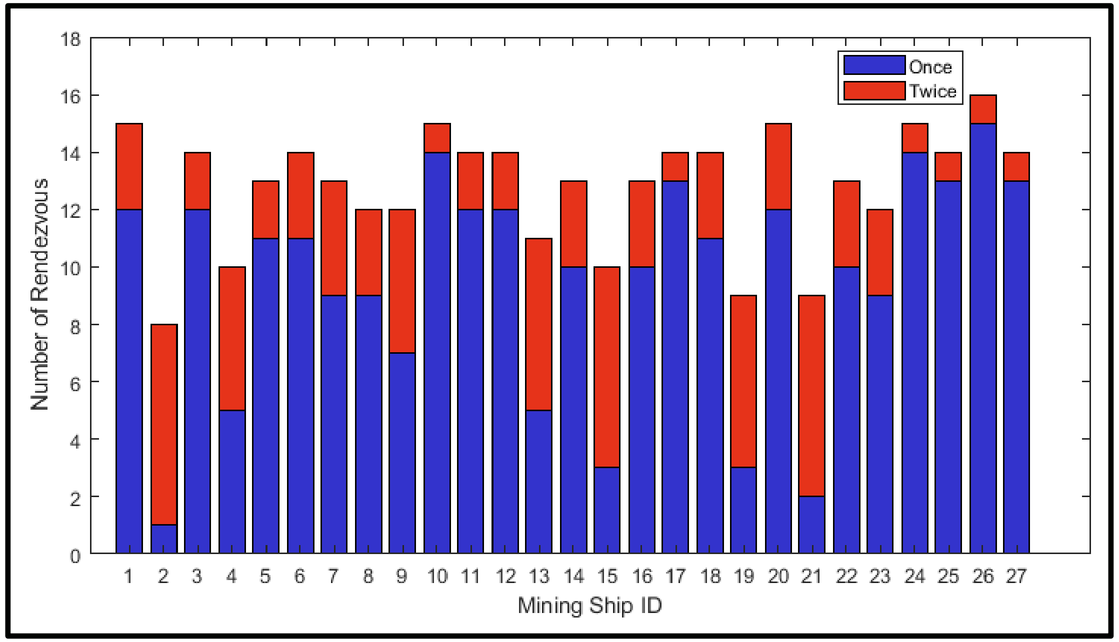


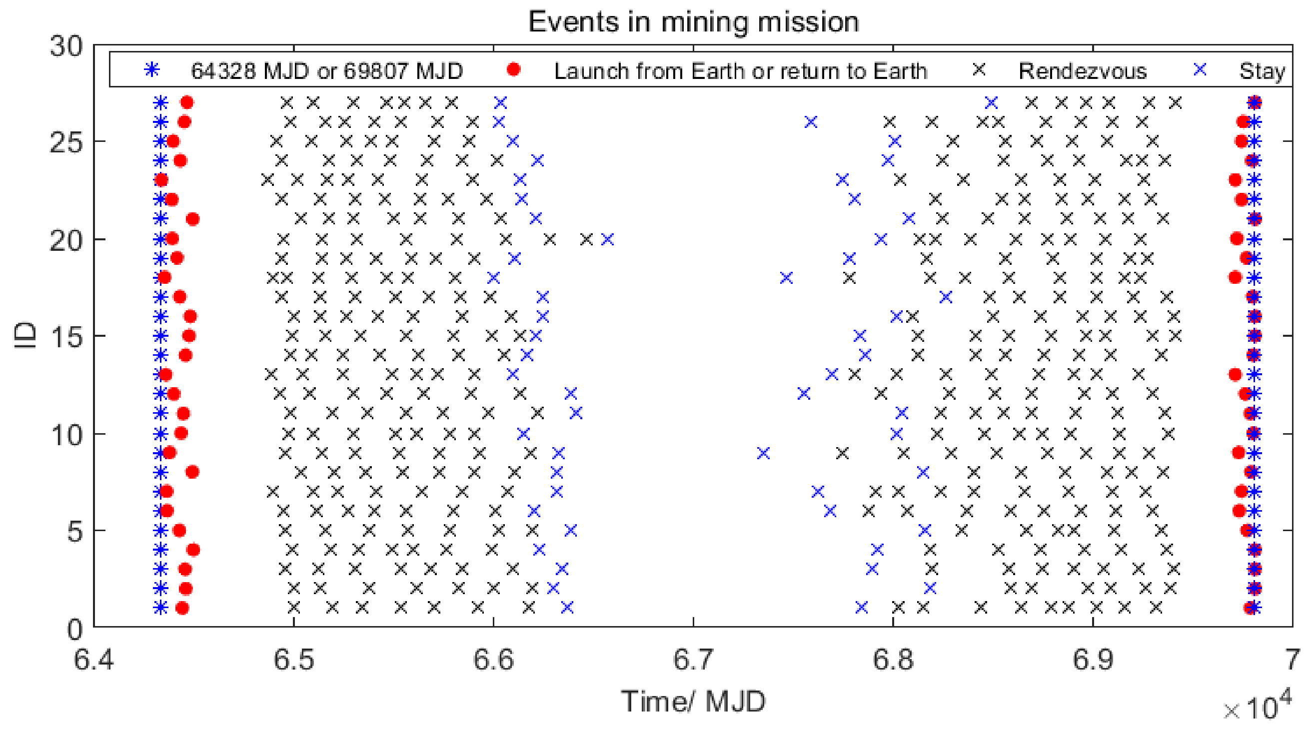



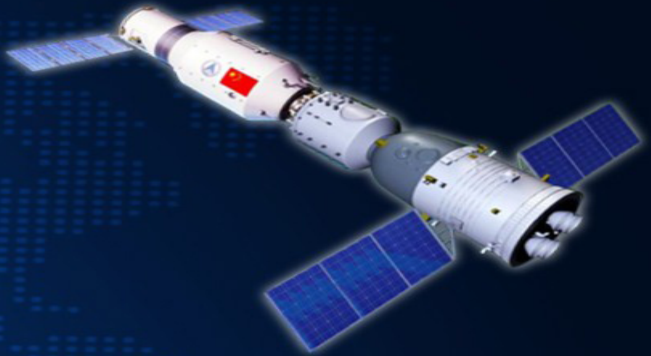
## 3 Better solution after the competition

- The average mind mass has been increased by 3.98%.
- 3 more ships can be used and the average mined mass can reach 677 kg.

| | $\sum_{i=1}^{60000} M_i$(kg) | $\bar{M}$(kg) | Improvement | $N_{max}$ |
|---|---|---|---|---|
| Original solution | 17591.9 | 651.55 | / | 27 |
| New solution | 18292.1 | 677.49 | 3.98% | 30 |





# Many Thanks!