Problem Chosen	2022 MCM/ICM Summary Sheet	Team Control Number
F		2218444

Equity in Outer Space: Asteroid Mining for all Mankind

The Outer Space Treaty of 1967 has stated the public nature of asteroid resources, and most of the world's nations has signed onto it. The treaty has provided articles to regulate the use of outer space and encouraged scientific researches for the benefit of all countries. However,asteroid mining,which will bring back valuable minerals and potential huge profits, has posed challenges to global equity. There is only one outer space for all mankind and how to determine whether asteroid mining corresponds to the benefits of all mankind? How can we promote global equity by updating Outer Space Treaty? To solve the problems,we complete following tasks:

- We define "Global Equity" with two fairnesses–the fairness for each and the fairness for the general whole. Equity makes sense only when the profits for each and the balances among all are both considered.Then we build "Double-Fairness Measuring Model" to evaluate global equity.The first sub-model"Actual Return on Investment"(AROI) is based on the **Return on Investment Model** in economics, but we consider different forms of return and calculate "Actual Return" which reflects the return in scientific development, in economy and other possible return at the same time.To determine the weight of different types of return,we use **Analytic Hierarchy Process(AHP)** In the same way, we calculate the total investment.As for fairness for the general whole,we calculate Relative Deprivation Index based on the **Relative Deprivation Theory** in psychology to evaluate the degree of equity for the general whole.After that,we validate our model with historical data in natural gas, which reflects that the degree of global equity is relatively high in this field.

- We predict the future vision of asteroid mining.We **divide it into two periods**-one mainly for scientific research and the other is the commercial period.We describe them from three aspects–how it is funded,who will perform asteroid mining and who will get the benefits.During the prediction, we use **Fuzzy Comprehension Evaluation Method(FCE),z-score and Jensen-Shannon divergence** to process the data.It is worth noting that we also discuss the significant differences between the two periods and the new additional task on environmental protection.The measuring model is used again to measure global equity.Unfortunately, it shows that asteroid mining will have negative effects on global equity.

- we then discuss the different impacts on global equity when different conditions change.As predicted, the scientific skills, which will affect the possible funders and possible performers , outweigh other indicators.Therefore,we conclude that it is necessary to help those countries with lower scientific skills to promote global equity.

- Next, we propose recommendations to update "Outer Space Treaty" from three aspects:Open data,fair evaluation and fairness in action and supervision.

- Finally,we make sensitivity analysis and present relative results.

Keywords: Global equity,asteroid mining,Return on Investment Model,Analytic Hierarchy Process(AHP), Relative Deprivation Theory,Fuzzy Comprehension Evaluation Method(FCE),"Outer Space Treaty"

Contents

1 Introduction

1.1 Background

As early as 1967, the United Nations' Outer Space Treaty has declared the principle of equity in exploring outer space — "exploration and use of outer space . . . irrespective of their degree of economic or scientific development, and shall be the province of all mankind".

However, problems rise as more and more countries and companies are looking to harvesting space-based resources. Nowadays, asteroid mining has become an important topic and bring challenges to equity. All countries share equal right in outer space but their abilities to explore and harvest the resources differ. How can we respect the efforts made by those bringing minerals back and the right of those unable to explore outer space at the same time?

Unfortunately,the previous international treaty—the United Nations' Outer Space Treaty—has not completely cover this field. To maintain outer space for worldwide equity in outer space, we need to make recommendations to update the "Outer Space Treaty". We hope to promote global equity in terms of allocation and find a path towards a shared future.

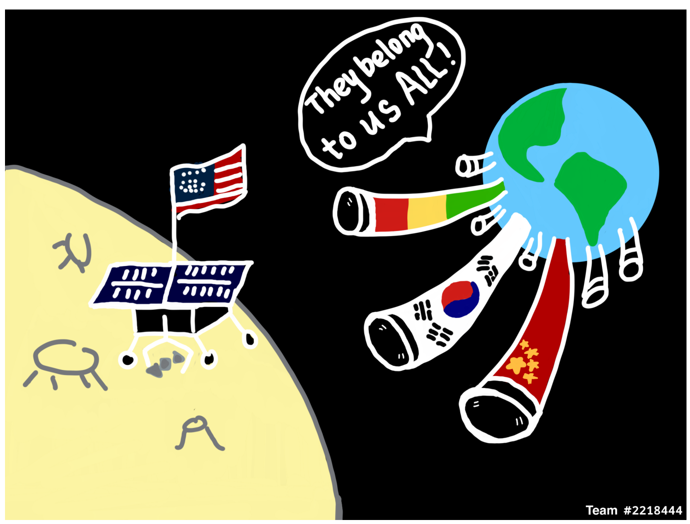


Figure 1: Background

1.2 Analysis of the Problem and Our Work

To better address the problems, we analyze the problems and divide our work into five steps:

- *Defining*. Different from the providing identical inputs, equity is the fairness in terms of allocation. So at first, we specify the definition of "global equity". In our eyes, in the global affairs, neither the efforts made by investors nor the different situation of different countries cannot be ignored.
- *Modeling*. The definition expressed in words is still vague, so we build a model to measure it, which pay attention to both the proper profits for contributors and the worldwide fairness. And the model is validated with historical data.?????
- *Predicting*. Since asteroid mining is not completely feasible nowadays, we imagine the future vision of asteroid mining. Here we measure its degree of global equity with our "Double-Fairness Measuring Model".

- *Discussing*. To explore the effects of different conditions of the future vision, we discuss how the changes of each condition will impact global equity. And this process leads us to find out the best status of each condition.
- *Updating*. At last, we give recommendations to 'Outer Space Treaty" based on the discussion and the "Double-Fairness Measuring model". Here, the reality and the future trend are both considered. Since it is not feasible to amend an international treaty too frequently, we try to predict the future and take a long period of time into consideration.

To better demonstrate our thoughts, we design the illustration below.

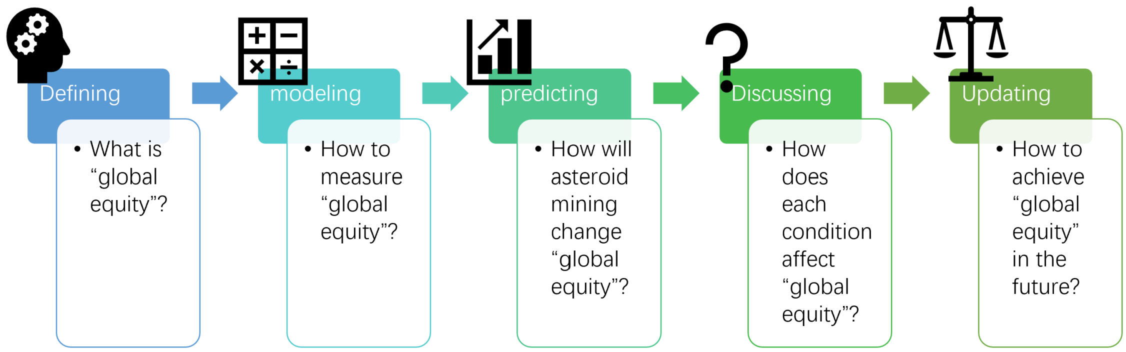


Figure 2: Workflow

2 Assumptions of Our Models

We make the following basic assumptions to simplify the problem. Our assumptions won't make essential distinctions to the problem and are based on the reality.

- Asteroid mining is technically feasible and the minerals can be brought back to Earth relatively safely.
- Asteroid mining is financially worth the investment. It is profitable and those countries with economic ability are willing to invest, even if they are not technically capable.
- The minerals brought back from outer space is divisible, and the loss coming from transportation can be ignore compared with the profit it brings.
- The fee of transporting the minerals is too little compared with the profits, and the countries are willing to pay it themselves.
- The minerals can be allocated to each participants with no rest for its huge additional value (in scientific research...).If a country wants money from the sales, there will be countries willing to buy.Vice versa.

3 Notations and Signs

Notations	Meaning
I_{AROI}	index of actual return on investment
R_a	actual return
R_m	Current monetary value of minerals
R_t	Profit from the temporary storing
R_e	Contribution to economy (GDP)
R_s	Scientific or innovative value of the minerals
I_b	Investment in Business
I_s	Investment in scientific research
I_P	Input in the process of mining
I_o	Investment from the ownership of the resources
I_e	Energy intensity of the economy (TPES/GDP)
σ	Standard value of Price Earnings Ratio(P/E or PER)
D_i	Relative Deprivation Index of the i^th participant
I_i	I_{ROI} of the i^th participant
N	Total number of participants
n_i^+	The number of the participants with higher I_{ROI} than the i^th participant
$\bar{I}_i^+$	Average I_{ROI} of those participants with higher I_{ROI} than the i^th participant
$\bar{I}$	Average I_{ROI} of all the participants
λ_i^+	Proportion of those with higher I_{ROI} than the i^th participant in the whole group
I_f	Funding Index
A_g	Score for GII(Global Innovation Index)
A_s	Index for the ability to launch satellite independently
A_i	Index for the ability to launch interstellar probe independently
A_c	Index for the ability to manufacture carrier rockets independently
A_m	Index for the ability in manned Spaceflight
A_p	General Index for the ability to perform asteroid mining

4 Problem 1:The Definition of "Global Equity" and the Measuring Model

4.1 The Definition of "Global Equity"

Global equity, which focuses on the fairness in allocation, infers to the final status where each participant shares the benefits generally fairly, in consideration of the public nature of outer space and the participants' investment.

For the fairness for all mankind, we cannot treat asteroid mining as the game of "who mines who possesses". The public nature of outer space outlines the significance of allocating fairly for all mankind. As mentioned in the United Nations' Outer Space Treaty of 1967, "exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development". This statement reflects the public nature of the resources of the outer space. Therefore, we cannot make the participants' investment as the only factor in allocating the profits.

Also, if we ignore the participants' investment, it will lead to the unfairness to those countries (usually the developed countries or few developing countries with relatively strong power). since the profits push participants to explore the outer space harder, we cannot divide the profits roughly in equal amount either. This "naïve" action will undoubtedly lower the productivity and ignores the basic principle in marketing at the same time. Thus, we do not agree with the so-called "equity" which does not care about the profits of contributors.

As we all know, there is not such thing as absolute fairness, especially when we take the fairness for all mankind and the fairness for investors both into consideration. What we try to do is to find the balances—one between different participants, and the other between the contributions and the profits received actually.

Based on the definition, we develop **Double-Fairness Measuring Model** to measure the global equity .With the measuring model above, we can have a clearer vision on the definition of global equity.

4.2 The Presentation of the Double-Fairness Measuring Model

As mentioned above, our model considers two balances at the same time—one between the contributions and the profits received, and the other between different participants.

4.2.1 "fairness for investors"—AROI Model

First, let's consider the first balance—the balance between the contributions and the profits received—to realize the "fairness for investors".

We use the **"Actual Return on Investment"** (AROI) to indicate the balance between the contributions and actual profits. Different from ROI (Return on Investment) usually seen in business, AROI refers to the total profits after transforming the resources into economic or scientific values.

AROI calculates the ratio between investment and profit, indicating that whether the allocation is profitable for the investors. It shows the fairness for investors, usually the developed countries or few developing countries with relatively strong power.

AROI takes the innovative abilities, economic development and energy conversion efficiency into consideration. Therefore, it protects those developing countries with weaker technological ability. For example, in 2010, China's energy intensity of the economy (TPES/GDP) is four times that of Japan, which means the same amount of mineral contributes differently to different countries.

The following illustration presents the specific indicators used to calculate investment and profit.

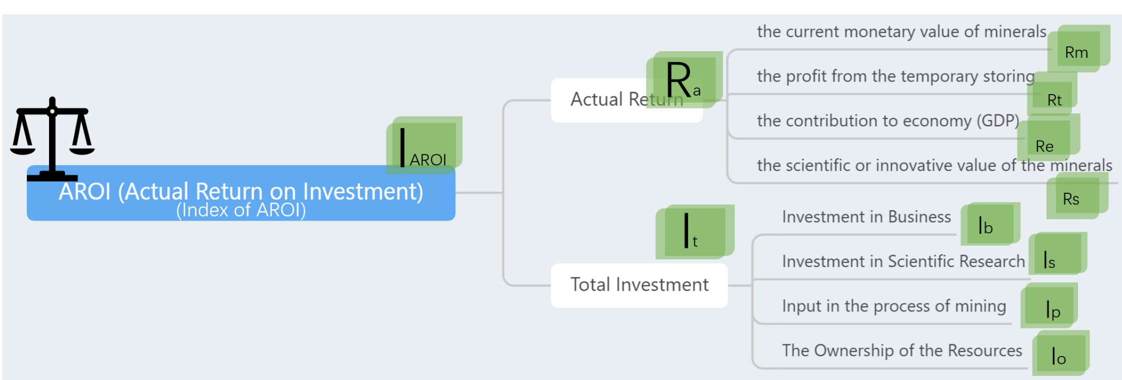


Figure 3: Problem 1 AROI

Now, each indicator will be explained.

1. Actual Return R_a
   Actual Return is the weighted sum of the current monetary value of minerals(R_m),the profit from the temporary storing(R_t),the contribution to economy (GDP)(R_e) and the scientific or innovative value of the minerals (R_s).
   We note their weight with w with the same subscript.

$$R_a = R_m \times w_m + R_t \times w_t + R_e \times w_e + R_s \times w_s$$

   (a) the current monetary value of minerals R_m
   We note the price of the mineral as P_m per unit.
   - If the country decides to sell the minerals away partly or wholly,it gets the current monetary value of particular part of minerals immediately.And the amount of the minerals sold is noted as M_s.
   - We note the amount of minerals unsold as M(and M_i if there are various types,$\sum M_i = M$),the total amount of minerals as M_t.
   - As for the current monetary value of minerals, there is **no** difference between those sold and unsold.**But the minerals sold have only current monetary value.For them, they don't have any other values(In other words,$R_t = R_e = R_s = 0$,$R_a = R_m$!)**
   - If there are varied types of minerals, we use P_{mi} and M_{ti} as notations($\sum M_{ti} = M_t$).And we suppose there are n types of minerals in all.

$$R_m = M_t \times P_m R_m = \sum_{i=1}^{n} M_{ti} \times P_{mi} \tag{1}$$

   (b) the profits from the temporary storing of the minerals R_t
   Consider that some countries might store the minerals when the price is relatively low but sell the minerals out if the price go higher.Just as how people treat stocks and government bonds.
   We use the Price Earnings Ratio(P/E or PER) in the stocking market to simulate it.

$$PER = the\ \ price\ \ of\ \ stock/the\ \ net\ \ profit \tag{2}$$

   $PER = 10$ is thought to be too lower and $PER = 20$ too high.So we choose $PER = 15$ as the standard value.We note is as σ.

$$R_t = \sigma \sum_{i=1}^{n} P_{mi} M_i \tag{3}$$

   (c) The economic contributions made by minerals R_e
   It can be calculated as the product of **energy intensity of the economy (TPES/GDP)** and the amount of the minerals.

$$R_e = M/I_e \tag{4}$$

   ,where we note TPES/GDP as I_e. The same with R_f, if n>1:

$$R_e = \sum_{i=1}^{n} I_{ei} M_i \tag{5}$$

   (d) The scientific value of the mineral R_s
   We use as the **ratio of Research and Development(R&D) Input to GDP** as a criteria.

$$R_s = M \times P_m/I_{RD} = \sum_{i=1}^{n} M_i \times P_m/I_{RD} \tag{6}$$

   ,where we note the ratio of Research and Development(R&D) Input to GDP as I_{RD}.

(e) Each Indicator's Weight

In reality, the scientific value and the direct financial value do not weight the same for a country. The scientific value is vital for those countries struggling to break through technology blockage. So it is unreasonable to add the profits up directly.

Here, we use **Analytic Hierarchy Process(AHP)** to determine each indicator's weight,as the factors do not have clear boundaries,for example R_s may influenceR_e.(The numeric results will be showed in the section"Validation of the Measuring Model".And the Matlab code is in the appendix.)

2. Total Investment I_t

Total Investment is the weighted sum of monetary investment and The investment by giving out ownership.

(a) Investment in BusinessI_b

I_b equals the money input to support the business or buy the products .

(b) Investment in scientific researchI_r

I_r refers to the invest in supporting scientific research.

(c) Input in the process of mining I_p

For those performers (who do the mining),there are cost generated from the process of mining,for example,the salary for the personnel the cost of repairing instruments. We use the existing data for the cost of extracting the mineral per unit. So we have:

$$I_p = C_p \times M_e$$

$$I_p = \sum_{i=1}^{n} C_{pi} M_{ei} \tag{7}$$

,where M_e refers to the total amount of minerals extracted.

(d) I_o

The investment by giving out ownership refers to the sales or the rent of the ownership.

$$I_o = k \times V_o \tag{8}$$

$$k = \begin{cases} 1, & \text{if } the\ country\ gives\ it\ away; \\ 0, & \text{if } the\ country\ uses\ it\ itself. \end{cases} \tag{9}$$

(e) Each Indicator's Weight(For Total Investment)

Investments of different types do not weigh the same for a country.For example, a country can get immediate profit from I_c(Input in the process of mining),but it can hardly get profit from I_r(Invest in scientific research) in a short time.The different kinds of investment should be weighed.Similarly, we use **Analytic Hierarchy Process(AHP)** to decide the weight.(The numeric results are shown in the next section.)

Now we can calculate I_{AROI}.

$$I_{AROI} = \frac{R_a}{I_t} = \frac{R_m \times w_m + R_t \times w_t + R_e \times w_e + R_s \times w_s}{I_b \times w_b + I_r \times w_R + I_p \times w_p + I_o \times w_o} \tag{10}$$

4.2.2 "fairness for all mankind"—Relative Deprivation Model

Let's consider the second balance-the balance between different participants-to realize the "fairness for all mankind".

Based on "Relative Deprivation theory" raised by American scholar S.A Stouffer,we develop a model called "Relative Deprivation Model" to measure the degree of equity in a specific group.

The sense of relative deprivation rises when participants see those who earns more than themselves.It is unreasonable to compare the profits without considering the inputs. So we use the I_{ROI} ,which indicates the ratio of actual return to total investment, as original data.

We note:

Table 1: The notations in the Relative Deprivation Model

Notations	Meaning
d_i	the Relative Deprivation Index of the $i^t h$ participant
I_i	theI_{ROI} of the $i^t h$ participant
N	the total number of participants
n_i^+	the number of the participants with higher I_{ROI} than the $i^t h$ participant
$\bar{I_i^+}$	the average I_{ROI} of those participants with higher I_{ROI} than the $i^t h$ participant
$\bar{I}$	the average I_{ROI} of all the participants
λ_i^+	the proportion of those with higher I_{ROI} than the $i^t h$ participant in the whole group

Here comes the equation:

$$\begin{aligned} d_i &= \frac{(n_i^+ \times \bar{I_i^+} - n_i^+ \times I_i)}{N\bar{I}} \\ &= \frac{\lambda_i^+(\bar{I_i^+} - I_i)}{\bar{I}} \end{aligned} \tag{11}$$

4.2.3 The standard of Global equity

We collect all "Relative Deprivation Index"s in a data set$D$.To analyze the degree of equity through "Relative Deprivation Index", we focus on the average, range and standard deviation of the data set D. But there is no given standard for these three parameters.Therefore,we refer to the Olive-shaped structure in economics. We suppose that the degree of global equity is relatively high when the data structure are **olive-shaped**.(We believe that it is impossible that I_{AROI}s of all countries are the same.And it is meaningless to consider this status.)

So we will draw the ellipse of the equation below and compare the data with this standardized ellipse.

$\frac{(x-m)^2}{a^2} + \frac{(y-\bar{d})^2}{b^2} = 1$

,where $\bar{d}$ is the average of the Relative Deprivation Index$d$ of all countries in this status. a is standard deviation of d of all countries. b is the half of the range of d of all countries.m is used to control the position of the ellipse.

4.3 The Validation for the Measuring Model

4.3.1 Data Input

To validate our model,we choose the historical data of natural gas in 2020 for the following reasons.

- Not all countries can extracting natural gas themselves, just like not all countries can do asteroid mining themselves.
- National governments and private companies are both involved in extracting natural gas as funders or performers,just like both national governments and private companies are involved in asteroid mining.
- Governments and private companies can choose to participate in the extraction through funding and performing extraction.
- Different countries may involved in one extraction action,similar to asteroid mining.

Here are the data corresponding to each indicators mentioned above.

1. Actual Return R_a

Table 2: Actual Return

Factors	Weight	Canada	USA	Brazil	France	Germany	Russia	Iran
R_s	0.565	44.54	70.975	26.5459	41.5	43.353	44.979	31.7115
R_m	0.2622	18.8862	100	3.5834	1	1.512	70.116	28.1461
R_e	0.1175	10.792	52.2685	3.0698	1.0177	1.4152	85.058	49.1470
R_t	0.0553	36.0952	75.0367	1.0079	5.4646	25.7711	100	7.2321
R_a	1	33.3812	76.612	16.3544	24.1315	26.4823	59.3219	31.4716
Factors	Weight	Saudi Arabia	China	India	Japan	Korea	Africa	UK
R_s	0.565	27.136	46.5957	28.1958	41.2139	44.7302	29.1604	46.1667
R_m	0.2622	13.1439	21.9829	3.5834	1.3557	1.021	26.0415	5.267
R_e	0.1175	19.1684	13.2423	2.2917	1.1778	1.0105	22.5224	4.7782
R_t	0.0553	91.49	3.5315	1	1.0094	1.0015	13.3325	5.7088
R_a	1	26.0899	33.8417	17.1948	23.8355	25.7144	26.6874	28.3423

2. Total Investment I_t

Table 3: Total Investment

Factors	Weight	Canada	USA	Brazil	France	Germany	Russia	Iran
I_b	0.1172	15.8618	46.9140	4.84589	30.2555	100	12.7768	1
I_r	0.2684	2.1525	20.8573	3.63180	3.92797	1.85810	27.3391	1
I_p	0.6144	25.7788	76.1986	9.5712	7.1146	14.5886	53.5014	46.1096
I_t	1	18.2753	57.9129	7.42325	8.9714	21.1820	41.7066	28.7153
Factors	Weight	Saudi Arabia	China	India	Japan	Korea	Africa	UK
I_b	0.1172	1.1677	89.0797	22.7353	69.2540	35.2137	1.32846	28.8479
I_r	0.2684	5.51185	21.3656	8.69242	44.6672	100	98.7578	1.6095
I_p	0.6144	14.3936	17.6573	5.5636	1.5765	1.01575	19.7843	19.4833
I_t	1	10.4597	27.0233	8.4160	21.0738	31.5911	38.8177	15.7835

3. Index of Actual Return on Investment I_{AROI} and Index of Relative Deprivation d

Table 4: Index of Actual Return on Investment I_{AROI} and Index of Relative Deprivation d

	Canada	USA	Brazil	France	Germany	Russia	Iran
I_{AROI}	1.82658	1.3229	2.2031	2.6898	1.2502	1.4224	1.0960
d	0.0964	0.2367	0.0353	0.0000	0.2632	0.2051	0.33481674
	Saudi Arabia	China	India	Japan	Korea	Africa	UK
I_{AROI}	2.4943	1.2523	2.0431	1.1310	0.8140	0.6875	1.7957
d	0.0089	0.2624	0.0571	0.3173	0.4884	0.5631	0.1034

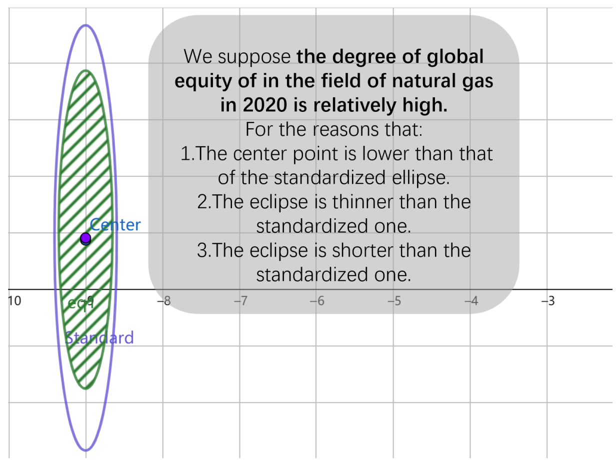
4.3.2 Judgement of "Global Equity"

Here we use the standardized ellipse to make comparison.

Table 6: Data for the Judgement of "Global Equity"

Average d	0.212298901928571
Range of d	0.563072392000000
Standardized Deviation of D	0.175021006748887

(a) Data for the Judgement of "Global Equity"



(b) Judging "Global Equity" with ellipse

Figure 4: Judgement of "Global Equity"

5 Problem 2:The Likely Future Vision of Asteroid Mining and Impacts on Global Equity

"Future" is a vague notion in scientific research and modeling. "Future" is infinite and It is impossible to describe it year by year.But we suppose that the prediction exposing the rule of development is valuable.

Thus,we discuss "future" as two periods-period mainly for scientific research and the commercial period.These two periods can cover a quite long time.

5.1 Descriptive Conditions

Here we choose three conditions to describe the two future periods.

- **Funding**-how asteroid mining is funded?
- **Performers**-who is doing the mining?
- **Beneficiaries**-who will get the benefits for minerals themselves or the profits from the sales?

5.2 Period Mainly for Scientific Research

In this period,although the researchers can bring back some minerals, the amount should be small. The immediate profit is almost zero.The main profit (potential) of this period is the contributions to commercial period, in other words, will come in the commercial period.

5.2.1 Funding-how asteroid mining is funded?

As mentioned in the document N9631342 of UN General Assembly(Session 4)," States are free to determine all aspects of their participation in international cooperation in the exploration and use of outer space on an equitable and mutually acceptable basis."And based on the current market rules,international laws and current situation in marketing, we suppose that asteroid mining is funded freely.

However,although every country has the right to fund, not all have the ability. So we predict the possible main funders here.

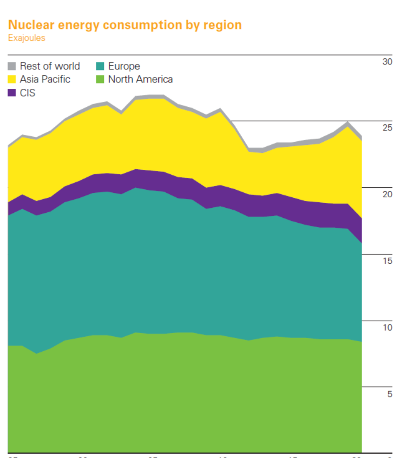
1. **National Governments**

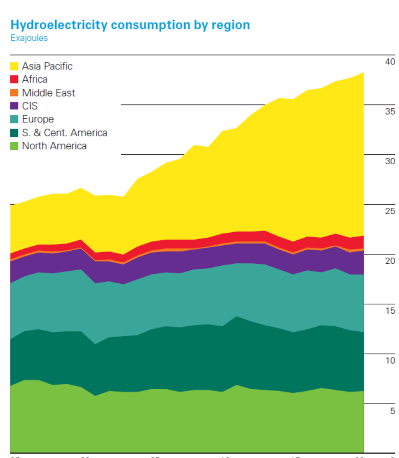
   National Governments will usually be the main pushing force at the initial stage of resources exploitation.We predict the countries most likely to fund in three dimensions:

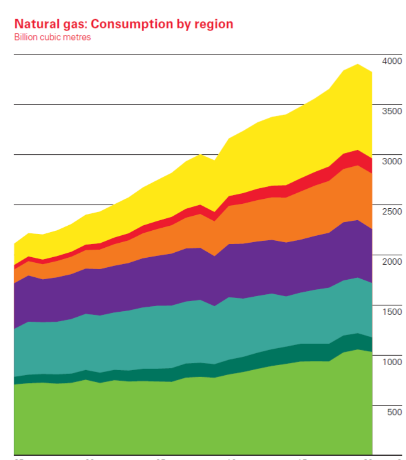
   (a) Motivation to fund-Lack in resources

   We suppose those countries in lack of resources will be eager to participate in funding to get the profits in the future.

   As asteroid mining is relatively new branch of resource sector.We use the historic data of other resources to see which countries/regions are more in lack and predict their future needs.







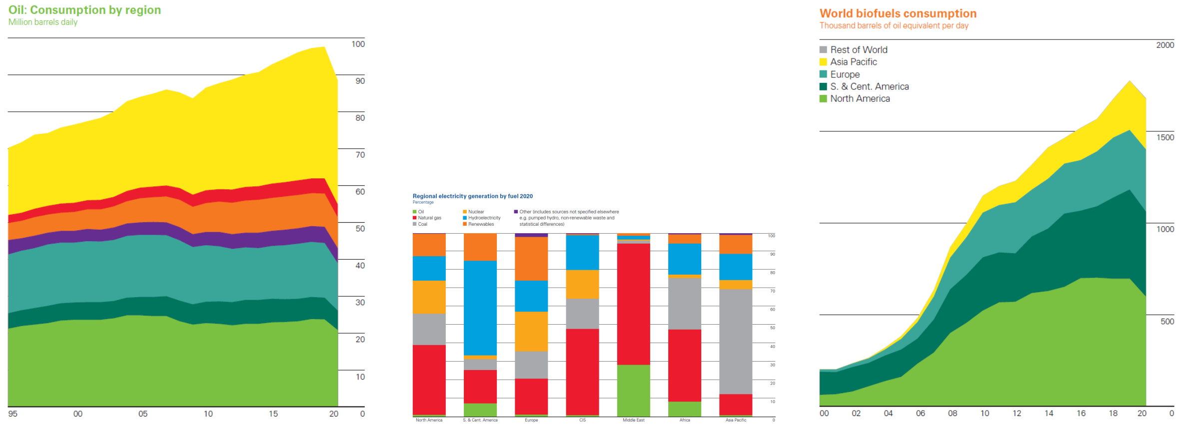


Figure 5: The Global Consumption of Resources

As shown above, the consumption of different types of resource in the same region is similar in percentage.And the growth trends are similar for different countries. We can conclude that the average condition of different types of resources can reflect the lack for resources in different regions.So it is reasonable to use the average trend to predict the national governments which are most likely to fund for asteroid mining.

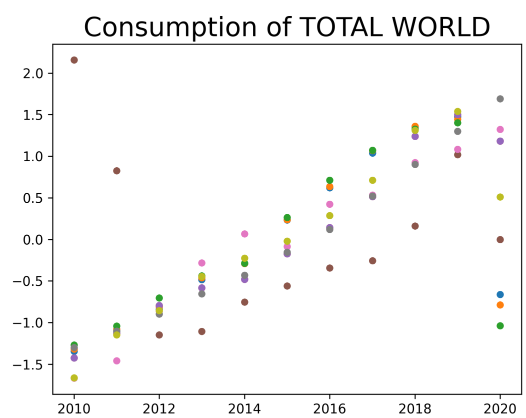


Figure 6: Predicting the Resources Consumption with JS compared

Here, we use Jensen–Shannon divergence.The Matlab Code is in appendix.(The factor"Primary energy"x_9 in code is standardized with z-score method.)

- Calculate Jensen-Shannon divergence of every two resources.
- For one particular resource,add up the Jensen-Shannon divergence between itself and every other type of resource. We call the addition as "General Jensen-Shannon divergence" of particular resources.
- Compare the "General Jensen-Shannon divergence".Choose the consumption trend of the resource with the minimum "General Jensen-Shannon divergence" as the general condition of lack in resources for different regions.

The results are shown as followed.

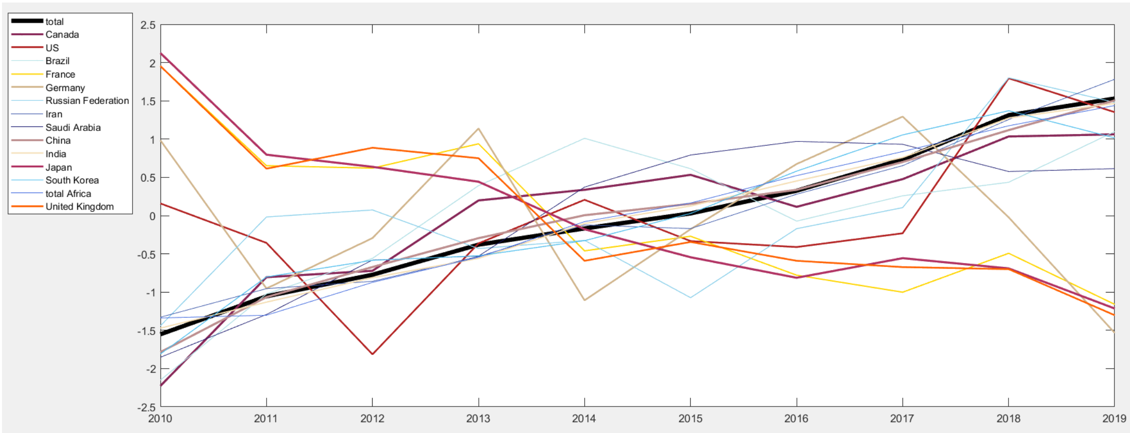


Figure 7: Global Consumption

(b) Economic Strength-Economic Development

It is supposed that a country with higher GDP has stronger economic strength. We score their economic strength according to the global ranking of their GDP.

Table 5: Economic Strength

	Canada	USA	Brazil	France	Germany	Russia	Iran
Ranking	8	1	11	7	4	9	13
Scores	0.6	1	0.4	0.6	0.8	0.4	0.2
	Saudi Arabia	China	India	Japan	Korea	Africa	UK
Ranking	12	2	6	3	10	14	5
Scores	0.2	1	0.6	1	0.4	0.2	0.8

(c) Interests in Aerospace-Historical Actions in Aerospace

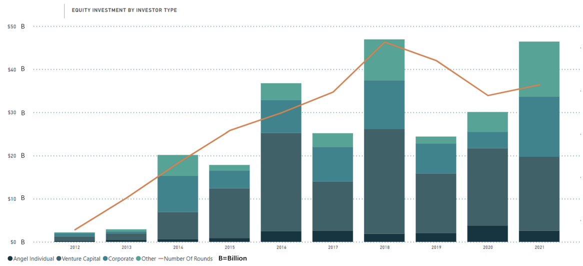
To better simulate the possible vision of funding in asteroid,we score the interest a country shows in aerospace according to the frequency it act in asteroid (the number of Satellites it has launched).

Table 6: Interests in Aerospace

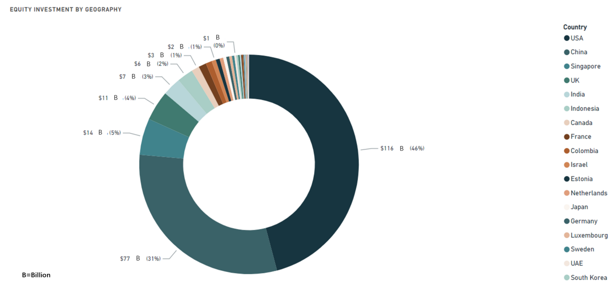
	Canada	USA	Brazil	France	Germany	Russia	Iran
Scores	0.6	1	0.2	0.4	0.2	1	0.4
	Saudi Arabia	China	India	Japan	Korea	Africa	UK
Scores	0.2	1	0.6	0.8	0.2	0.2	0.6

2. **Private Companies**

In fact,there are also some privates companies with economic and technological strength are willing to fund for aerospace.The data are shown below.



(a) Investment in Aerospace Besides Governments-1



(b) Investment in Aerospace Besides Governments-2

Figure 8: Investment in Aerospace Besides Governments

3. A Possible Funding List in General

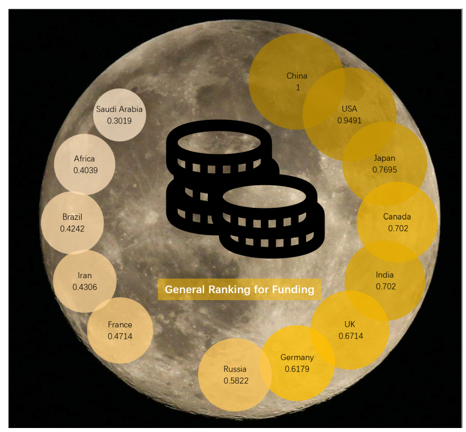
   To combine the three factors and decide the possible funding list,we use **Fuzzy Comprehension Evaluation Method(FCE)**.Here, as asteroid mining is still at researching period,we do not distinct the private companies and the national government.

   Then we calculate the weighted sum of the three factors and make a general ranking list.

Table 9: Each Factor's weight by FCE

Motivation	0.2548
Economic Strength	0.6115
Interests in Aerospace	0.1338

(a) weighted sum of the three factors



(b) Ranking List for Funding

Figure 9: Deciding Funding List

The numbers in the circle are right the weighted sums of the three factors.We note the weighted sum as "Funding Index"I_f.It reflects the possibility of funding.Its contrary side "No-Funding Index"$\bar{I_f}$ reflects the possibility of refusing to fund.
So if $I_f > \bar{I_f}$,the country is more likely to fund.As $I_f + \bar{I_f} = 1$,we take the countries with $I_f$higher than 0.5.
The final funding list(noted as F)is :

$$F = \{Canada, USA, Germany, Russia, China, India, Japan, Korea, UK\}$$

5.2.2 Performers-who is doing the mining?

As for aerospace(such a capital intensive industry), economic strength is the necessary condition for asteroid mining.But it is not a sufficient condition.Only the countries with both economic strength and scientific strength are able to perform asteroid mining.

So we will choose the possible performers from the possible funding list.

The choosing process is performed in two steps:

1. The **premise** of Performing Asteroid Mining-The Ability to Launch a Satellite Independently
   We treat it as the basis of performing asteroid.The possible funders without the ability to launch a satellite independently will be removed.
   Through searching,we got a list of the countries capable of launching a satellite independently.
   we note the list as set C.

$$C = \{Russia, China, Ukraine, UK, France, USA, India, Japan, Israel, Iran, DPRK\}^{1}$$

   Then we make the list P_1 by $F \bigcup C$:

$$P_1 = F \bigcup C = \{Russia, USA, China, India, Japan, UK\} \quad (12)$$

2. The General Ability to Perform Asteroid Mining A_p
   To specify the general ability(noted as A_p), we set specific indicators and decide their weights with **Fuzzy Comprehension Evaluation Method(FCE)**:

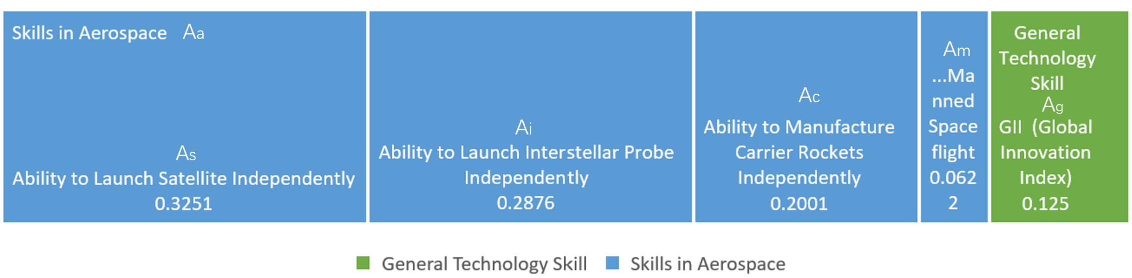


Figure 10: Weights of Factors for Evaluating Scientific Strengths

   It is worth noting that,although some countries have been removed from Performing List When we decide P_1,we still evaluate their general ability to perform asteroid mining to demonstrate the correctness of step 1(P_1).The factors are noted as shown in the figure above(Fig.8).

   Here,A_g is valued by their global ranking of GII.A_s,A_i,A_c,A_m by the time the country achieved it successfully. To standardize the data, we score them between 0 to 1 based on the original data(For A_g,higher ranking,higher point.The earlier it achieve,the higher point they get.

[1] Although it is not clear whether DPRK(Democratic People's Republic of Korea) has launched the satellite successfully, we put it in the list for the moment.

Table 7: The General Ability to Perform Asteroid Mining A_p

	Canada	USA	Brazil	France	Germany	Russia	Iran
Original data for A_g	8	1	11	5	4	9	12
A_g	0.6	1	0.4	0.8	0.8	0.6	0.4
A_s	0.2	1	0.2	0.8	0.2	1	0.4
A_i	0.2	1	0.2	1	1	1	0.2
A_c	0.2	1	0.4	0.6	0.2	0.8	0.6
A_m	0.2	1	0.2	0.2	0.2	1	0.2
A_p	0.25	1	0.265	0.7802	0.5051	0.91	0.3701
	Saudi Arabia	China	India	Japan	Korea	Africa	UK
Original data for A_g	13	6	10	7	3	14	2
A_g	0.2	0.8	0.6	0.8	1	0.2	1
A_s	0.2	0.6	0.4	0.8	0.4	0.2	0.6
A_i	0.2	1	1	1	0.2	0.2	0.2
A_c	0.2	0.8	0.6	0.8	0.6	0.2	0.6
A_m	0.2	1	0.2	0.2	0.2	0.2	0.2
A_p	0.2	0.8049	0.6251	0.8202	0.4451	0.2	0.5101

The general ranking as below:

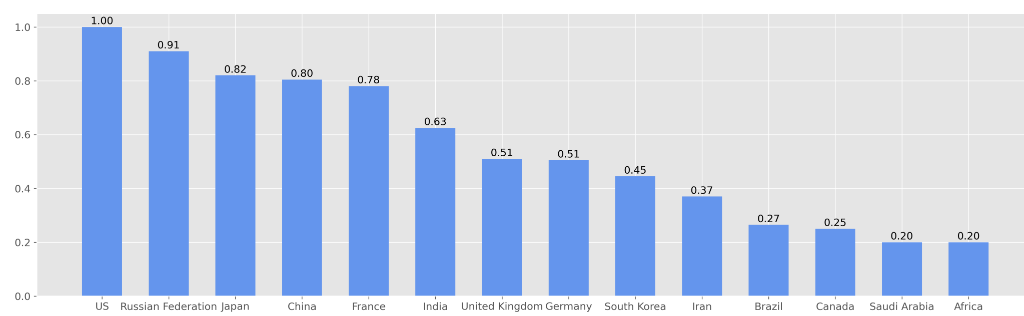


Figure 11: Ranking of General Ability in Asteroid Mining

We select those countries with A_p higher than 0.5 as the possible performers–**US,Russia,Japan,China, France,India,UK,Germany.**

5.2.3 Beneficiaries-who will get the benefits for minerals

- **For Performers**
  There is no significant economic profits.But their performance has raised confidence.In other words, it will be easier for them to attract funding at the coming commercial period.
- **For Funders**
  They will not get the profits immediately,as there is no significant economic profits for the moment. They will get profits in the commercial period in particular form based on their contract with the performers.Maybe they will hold some shares and get monetary return.Or they may get some research results as rewards.

However,it is worth noting that as the performers are capable both economically and technologically,the funders may not be dominant in the process of concluding the contract.

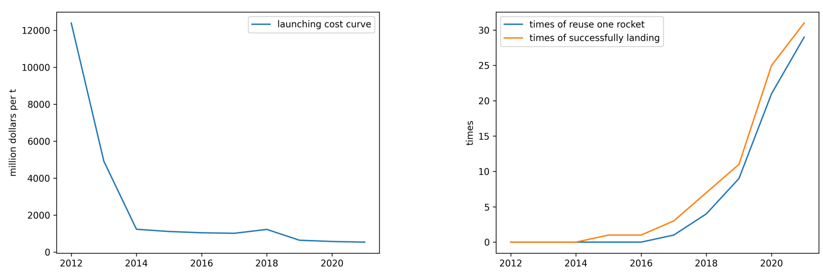
- **For Non-Funders and Non-Performance**
  In this period, there is no significant economic profits. And as the amount of mineral is small, we don't suppose the countries performing asteroid mining has violated the public ownership of asteroid resources.
  Therefore,they cannot ask for profit for their inherent ownership of asteroid resources.
  In a word,there is non profit for them.

5.3 Commercial Period

5.3.1 When will the Commercial period come

With the development of asteroid mining,we suppose that private companies will take a more active part in it.Also,for the commercial nature of private companies,we take the representative one from them as the indicator–SpaceX-Falcon 9.The commercial period comes :

- When its average cost of bringing one ton of mass from earth to the near-earth orbit C_b decreases to a relatively low and stable value.
- When the average cost C_b,the times of successfully landing(D_s) and the times of reusing aircraft are relative closely, and the closeness remains stable.



(a) C_b (b) D_c and D_r

Figure 12: Predicting When Commercial Period Will Come

Also, based on the prediction given in the article from the website of Massachusetts Institute of Technology,Which corresponds with our curves, we predict the commercial period will come after 2045.

However, we must notice the negative effect of COVID-19,which has erased the global development of almost ten years! Therefore,we postpone it,and suppose that the commercial period will come after 2055.

5.3.2 Differences Between the Two Periods-The Problem about Ownership Rises

As the ability of asteroid mining grows, we predict the capable countries will establish mining bases on asteroids,in order to extract minerals cheaply and efficiently.

Also,the performers of asteroid mining will be able to extract minerals from larger area of asteroid land and bring back more minerals.The performers themselves as members of humankind,share the ownership of asteroid resources with others.But how can we define the proper area of land one country can extract minerals from,which corresponds to its own share of the ownership without violating the others?

So we suppose that the countries will divide the asteroid land for each country,supervised by UN.We predict the regulations for division as followed:

- The land within l kilometres to a mining base belongs the constructors of the mining base.They can extract minerals in it for commercial or scientific use.The numeric value of l will be discussed on UN conference.We call this type of land as **"Exclusive Economic Zone"** for the moment.
- The other countries without mining base(including funders and non-funders), can also get a piece of land of the equal area–called "Exclusive Economic Zone"(EEZ),too.
- The land besides "Exclusive Economic Zone" remains public. It belongs to all mankind,it can only be used for scientific research.No one is allowed to extract minerals from it for commercial use.

Therefore,those countries without mining base can rent out its "Exclusive Economic Zone". And as asteroid mining will bring huge profits, we suppose that those countries with mining space are willing to rent the land in other countries Exclusive Economic Area,even if they need to build a new mining base to extract minerals.

5.3.3 The Areas for Mining-which areas can be used for Mining?

In this period,the countries with no share in mining bases can participate in asteroid mining by "renting out Exclusive Economic Zone" (EEZ) besides investing in the form of money. But the possibilities of renting out Exclusive Economic Zone differ for countries in different conditions.

- Constructors of mining bases(The performers of Asteroid Mining)
  They are almost impossible to rent out their EEZ, as the profits from asteroid mining outweigh the the rental.They will use their EEZ instead of renting out.
- Funders but not performers
  They are the countries with relatively strong economy and they are the potential performers.Therefore,they may not rent out their EEZ, if they are prepared to construct their own mining bases.
- Non-constructors and Non-Funders
  On the one hand,the asteroid land makes no profits for them;on the other hand, they are usually developing countries in lack of money.So they are eager to rent out the lands to get the profits.

To predict the proportion of land a country may rent out(noted as P_r),we consider their general ability in asteroid mining(A_g) and Funding Index(I_f).P_r=the Standardized result of the sum of the global rankings of A_g and I_f(Min-Max Standardization).

Table 8: The Proportion of Land a Country May Rent Out P_r

	Canada	USA	Brazil	France	Germany	Russia	Iran
Global ranking of A_g	4	2	11	9	6	7	10
Global ranking of I_f	12	1	11	5	8	2	10
P_r	0.5909	0	0.8636	0.5000	0.5000	0.2727	0.7727
	Saudi Arabia	**China**	**India**	**Japan**	**Korea**	**Africa**	**UK**
Global ranking of A_g	13	1	4	3	8	12	5
Global ranking of I_f	12	4	6	3	9	12	7
P_r	1	0.0909	0.3182	0.1364	0.6364	0.9545	0.4091

5.3.4 Funding-How Asteroid Mining is Funded

We suppose that the list of main funders will not change for the following reasons:

- The ranking of economic strength will not change enormously.
- The growth trend needs for resources will not change enormously based on the historical data before COVID-19.(COVID-19 has lower the consumption of resources, but after COVID-19 it will come back to the previous level.)

5.3.5 Performers-Who will do the mining

1. **The Possible List of Performers**
   Here we still suppose the list of performers will remain relatively stable in the near future.If there are new comers, it is predicted that they can only be those on the possible funding list of the previous period for scientific research:
   - Aerospace is a technology-intensive and capital-intensive industry.It is hard to catch up in a short period for those with low A_p.
   - Even if some countries become able to extract minerals from asteroid, their proportion is still quite small compared to those countries which have started mineral mining before commercial period.
2. **A New Task for Performers–Protecting asteroid environment**
   In the previous period, as scientific researches make little damage to outer space compare to the large-scale mining in the commercial period. We don't consider the pollution in outer space or the damage to asteroid soil. But in this period, we suppose that the pollution in outer space and the damage to asteroid soil will be considered by international institutes (Such as UN).And countries will form new treaty on avoiding pollution and recovering asteroid soil,just as how governments and society treats carbon emission nowadays.**So performers will recover asteroid soil and reduce pollution besides asteroid mining.**

5.3.6 Beneficiaries-who will get the benefits for minerals

Here we show our prediction with a pie chart.

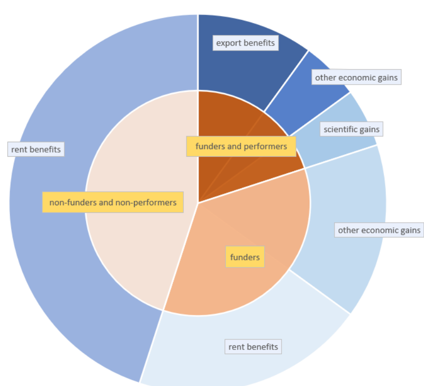


Figure 13: Problem2 Beneficiaries and the Structure of their profits

5.4 The Effects on "Global Equity"

- The Period Mainly for Scientific Research

  The main profits does not come in this period,and the scientific research does not violate the public ownership of asteroid resources,so it makes no sense to discuss its impacts on equity without considering the allocation of profits in the next period.

- The commercial Period

  To value its impacts on global equity,we predict "sub-factors" reflecting future conditions based on historical data. Our prediction is shown below.

Table 9: The Effects on "Global Equity"

	Canada	USA	Brazil	France	Germany	Russia	Iran
R_m	0.3537	0.9746	0.3446	0.6258	0.5615	0.7461	0.4003
R_t	0.01	0.3348	0.01	0.4658	0.2416	0.1064	0.01
R_e	0.3537	0.9746	0.3446	0.6258	0.5615	0.7461	0.4003
R_s	0.25	1	0.265	0.7802	0.5051	0.91	0.3701
I_b	0.7997	0.6397	0.4798	0.1599	0.3199	0.6397	0.7997
I_p	0.3537	0.9746	0.3446	0.6258	0.5615	0.7461	0.4003
I_r	0.4574	0.9491	0.4242	0.4714	0.6179	0.5822	0.4306
I_o	0.8261	0	0.8696	0.4783	0.4783	0.2609	0.7826

	Saudi Arabia	China	India	Japan	Korea	Africa	UK
R_m	0.251	0.9025	0.6636	0.7949	0.4856	0.3019	0.5907
R_t	0.01	0.1028	0.01	0.6349	0.01	0.01	0.2709
R_e	0.251	0.9025	0.6636	0.7949	0.4856	0.3019	0.5907
R_s	0.2	0.8049	0.6251	0.8202	0.4451	0.2	0.5101
I_b	0.4798	0.7997	0.7997	0.1599	0.7997	0.7997	0.3199
I_p	0.251	0.9025	0.6636	0.7949	0.4856	0.3019	0.5907
I_r	0.3019	1.0001	0.702	0.7695	0.5262	0.4039	0.6714
I_o	1	0.087	0.3043	0.1304	0.6087	0.9565	0.3913

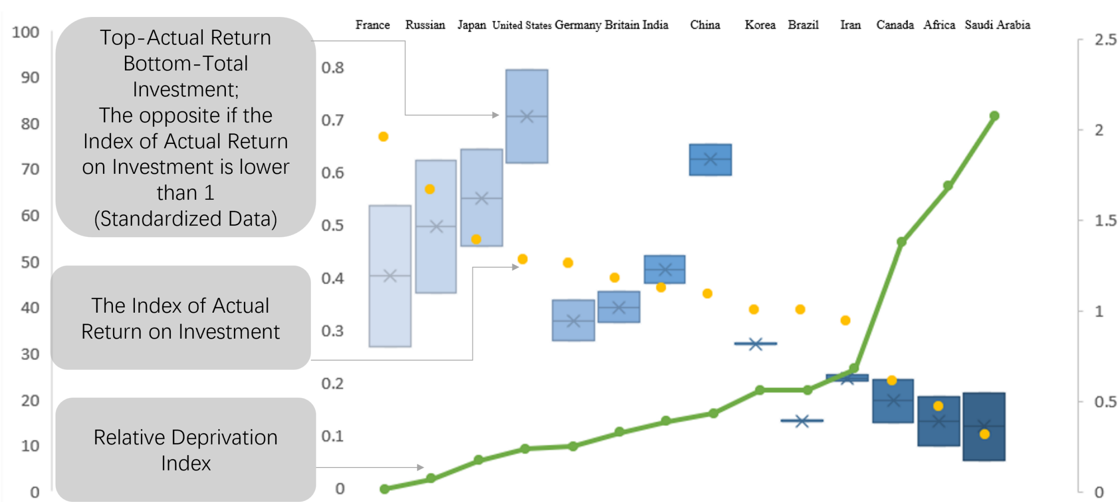


Figure 14: Predicted Status for Commercial Period

The average, range and standardized deviation are 0.212390004,0.70986419 and 0.216964282.Then we compare the corresponding ellipse with the standardized one. (Figure on the next page-G1&G9).The ellipse is fatter and the average of d(Relative Deprivation Index) is higher. We can conclude that asteroid mining **makes negative effect on global equity.**

6 Problem 3-Impacts of Changes on Global Equity

In this section,we change the conditions and present the changes with chart.The equation of the m^{th}ellipse is

$$\frac{(x-m)^2}{a^2}+\frac{(y-\bar{d})^2}{b^2}=1$$

,where$\bar{d}$ is the average of the Relative Deprivation Index$d$ of all countries in this status. a is standard deviation of d of all countries. b is the half of the range of d of all countries.And the 9^{th} shape reflects the status with highest degree of global equity,which is used to compare with.

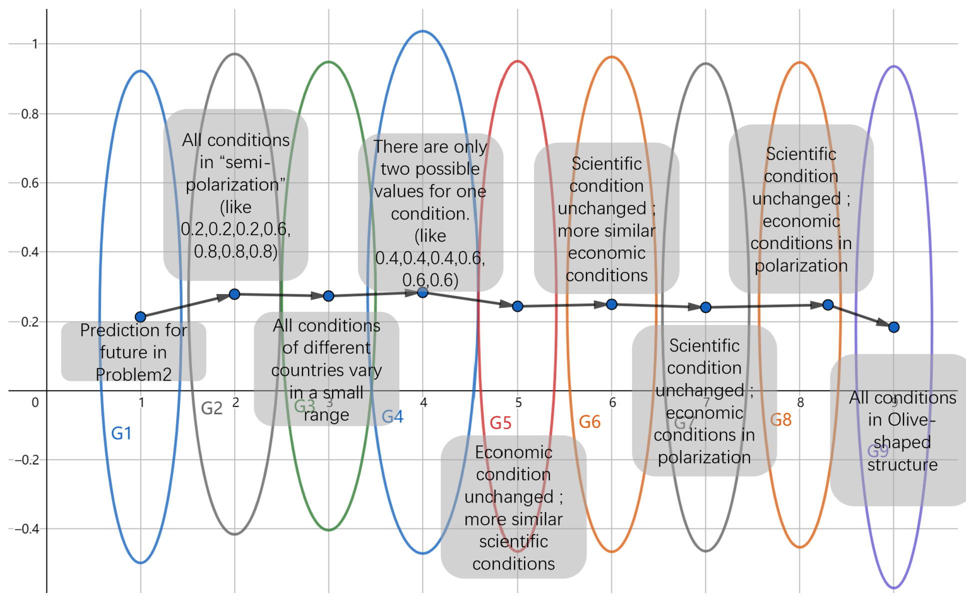


Figure 15: d in different conditions

- The comparison between economic and scientific conditions- G5 vs G6 and G7 vs G8
  The ellipse G6 is "fatter" than G5. The ellipse G8 is "fatter" than G7.The fatter ones reflect lower degree of global equity. So we conclude that **scientific conditions** matter more in global equity.
- The importance of the continuity of data-G4
  The ellipse G4 is the "fattest" one,which reflect the lowest degree of global equity. Compared with G2,we can conclude that **the general continuity of data** is more important than the data are concentrated partly.

7 Problem 4-Recommendation for Outer Space Treaty

We hope to promote global equity from three aspects:

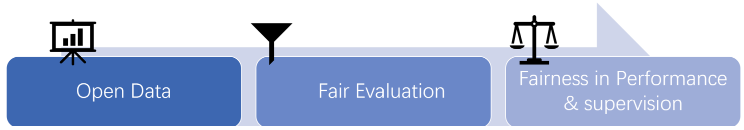


Figure 16: Three Aspects in Recommendation

A committee is required to realize the equity from these three aspects.

1. The ownership of the committee: The committee has 80% of public domain jurisdiction.
2. The composition of the committee:
   (a) the Council-selected from candidates nominated by member states
      i. The Legislation and Technical Commission
      ii. The Finance Committee
   (b) Member states-the countries willing to contribute to peaceful development and global equity
   (c) observers
      i. observer states
      ii. Intergovernmental organizations
      iii. Non-governmental organizations (NGOs)
   (d) The functions of the committee
      i. How the Legal Committee determines whether the applicant can mine on the basis of:
         A. Scientific and technological strength
         B. Economic strength
         C. There is no history of violating international conventions such as outer space treaty
      ii. How much money should be paid after the application is approved in order to fund the countries with poor scientific skills-considering their economic strength and technological level
         A. Environmental Performance Guarantee: including removal of any facilities and equipment; and the expenses for monitoring and managing residual environmental impacts after closure
         B. Mining royalties: Dedicated to providing financial assistance to less technologically advanced countries.
      iii. No entity other than the Contractor shall be permitted to develop or explore the same resource class within the contract area for the entire term of the development contract.
      iv. Contractors must provide transparent data reports within 90 days of the conclusion of mining activities (as discussed by the Committee)
      v. After each mining cycle, the Committee meets to discuss the contributions and benefits of each country during this mining cycle. An assessment is made that includes the following:
         A. The country's (production) during the mining cycle – for resource level statistics
         B. The country's direct cost of mining during the cycle
         C. The country's published information on space. Patents and scientific research achievements in mining.
         D. The cost of the country's investment in space mining technology and scientific research during the period
         E. The country's import and export trade volume of the output minerals during the period

F. The country's compliance with the Commission's regulations vii. Negative benefits of the country for the long-term development of space mining in this cycle (such as space junk, etc.)

vi. If any behaviors such as malicious price gouging of minerals is discovered, the country which commits it will be put into the blacklist of the committee.

vii. After each mining cycle, the committee should analyze the obtained data, evaluate the mining operation and the fairness of the distribution of benefits, publish an evaluation report on the mining operation and make all the data public.

viii. Member countries with financial and scientific research difficulties are allowed to participate in mining operations in the form of loans, and are allowed to apply for a certain amount of subsidies from the foundation.

8 Sensitivity Analysis

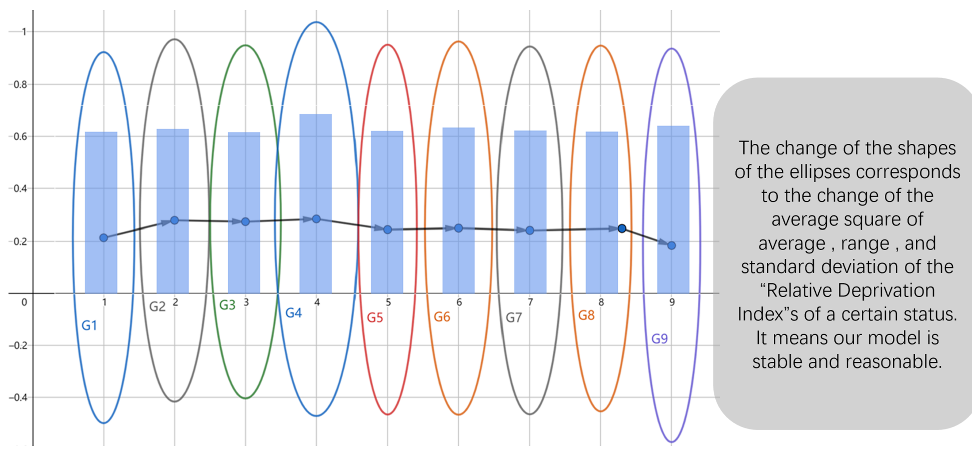


Figure 17: Sensitivity Analysis

9 Strengths and Weaknesses

9.1 Strengths

- Our Double-Fairness Measuring Model considers both the profits and equity.The model reflects our idea-Equity comes to life only when everyone shares profits. Equity and profits should neither be ignored.
- Relative Deprivation Theory in psychology is used to measure equity-which is hard to evaluate clearly.Also,it outlines the core of equity that it is not a absolute notion but relative.
- We use the olive-shaped structure in economics to value Relative Deprivation Index creatively.
- we predict the future as two main period-the period for research and commercial period.This prediction is clear and more similar to reality.

9.2 Weaknesses

- The original data set is not big enough as asteroid mining is a relatively new field.

- In problem 2,when evaluating a country's economic ability, we use GDP as the only factor and ignore the population and the economic structure.
- The standard of judging the degree of equity from d(Relative Deprivation Index) is not clear enough.

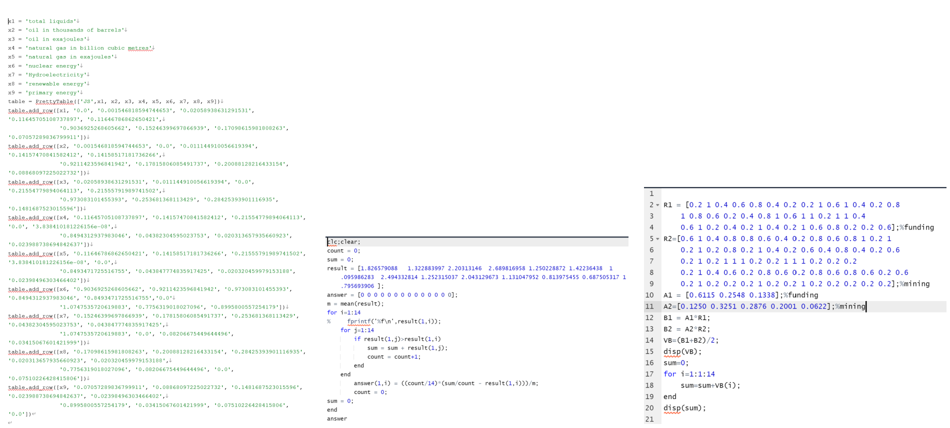
10 Conclusion

In this paper,we firstly define what global equity is–the fairness for each participant and the fairness of the general whole.Therefore,we then develop Double-Fairness Measuring Model to evaluate global equity,and validate it with the historical data of natural gas.We find the degree of global equity is relatively high in the field of natural gas.Secondly, we predict the future -the period for research and commercial period and use our Double-Fairness Measuring Model to judge their impact.We find that asteroid mining will make negative effects to global equity if the process is without interruption.Thirdly,we change the conditions to find the impacts of different conditions,from which we notice the most significant factor is scientific skills.Last,we sincerely write down the recommendations to Outer Space Treaty to promote global equity based on the findings in the previous problems.

References

[1] A possible new future alternative to land mining-Massachusetts Institute of Technology
https://web.mit.edu/12.000/www/m2016/finalwebsite/solutions/asteroids.html
[2]BP_Stats_2021-CEIC Data https://www.ceicdata.com/zh-hans/indicators
[3]wipo_pub_gii_2021-World Bank
https://datacatalog.worldbank.org/dataset/world-development-indicators
[4]Our Space-zhihu https://www.zhihu.com/question/355343818/answer/893409452?utm_source=wechat_session&utm_medium=social&utm_oi=1263177285446176768&utm_content=group3_Answer&utm_campaign=shareopn
[5]bp-Statistical Review of World Energy 2021
https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
[6]Space Capital-Space Investment Quarterly Q4 2021
https://www.spacecapital.com/publications/space-investment-quarterly-q4-2021

Appendix



(a) JS (b) AHP (c) FCE