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UNSRO: An Endeavor to Aspire Global Equity

Summary

Along with the rapid growth both in world population and STEM fields, the invisible pressure that the earth withstands escalates. The conflict between demanding more resources and damaging the ecosystem can no longer be neglected. However, collecting mineral resources from extraterrestrial objects, particularly asteroids, is a promising vision.

Different from the diverse mining industry regulations and structures in each country, not a single nation can claim ownership of any celestial bodies in outer space. Hence, like other common-pool resources, the global equity problem in resource distribution of asteroid mining remains unsolved. The metrics to assess the global equity level and concomitant policy formation methods are of substantial importance.

At first, we establish a set of global equity metrics, assess global equity through two dimensions: Resource Governance (RG) and Sustainability Impact (ST). For each dimension, there are multiple indicators. DT, PI, FM, AO for Resource Governance dimension and EI, SI, PP for Sustainability Impact dimension.

To illustrate our vision of the future asteroid mining industry, we presumed the existence of an international organization named the United Nations Space Resource Organization and establish the UNSRO model. In specific, the working procedure, resource distribution method, and division of labor are established to safeguard global equity. Based on multiple game theory models, we establish the Equity, Reciprocity, and Competition model to further justify the necessity of the existence of UNSRO by making comparisons with the traditional mining industry in terms of global equity. Moreover, we conducted a sensitivity analysis on this model to show its stability.

Furthermore, we selected seven representative nations in Africa to conduct a regional analysis, including the Democratic Republic of Congo, Ghana. Nigeria, Senegal, Tanzania, Tunisia, and Uganda. Based on their data sets matching our indicators, we applied Bayesian Estimation combining the Best-Worst method to determine each indicator’s weight. In the RG dimension, DT weights the most, the three other indicators have no significant difference. In the ST dimension, PP, SI, EI are in a decreasing sequence.

Concomitantly, we make policy suggestions in response to each indicator’s weight: in the RG dimension, the data transparency should have no disclosure, effective risk management should be conducted. In the ST dimension, the rule of procedure should be enforced, labor forces’ well-being should be fully considered, and possible space pollution should be prevented.

Finally, we discuss some possible fields where our model may be applicable, such as satellite orbit shells’ allocation and deep-sea resource distribution.

Keywords: Game Theory, Common-pool Resource, Bayesian Estimation, Best-Worst Method, Equity Theory

Contents

1. Introduction

1.1 Problem Background

The development of human society requires a steady input of resources, which brought the mining industry into existence. However, excessive mining activities have impinged negative impacts on our environment. Major environmental impacts include water accessibility and quality, air quality, land disturbance, waste generation, biodiversity loss, nuisance and disturbance according to the conducted CSIR-Central Institute of Mining and Fuel Research[1]. A reasonable thought is to find alternative resources, which introduced the possibility of asteroid mining, for Near-Earth Asteroids (NEA) may contain enough volatile and high-value minerals to make the mining process economically feasible and worthy[2]. Even though this idea is inspiring, we still have many problems ahead, and global equity is among them as a major political problem.

Of note, while we are still on earth, global equity has been debated in many different contexts. In mining, rare resources, such as rare earth, sometimes become political tools, when countries restrict access to them to get their way[3]. Even though asteroid mining may bring abundance in mineral resources, it's still dispensable to address the global equity problem, to avoid problems unforeseen.

1.2 Literature Review

Equity is a thoroughly studied topic in social science, which covers a wide range including gender equity, education equity, financial equity et cetera[4]. In this essay, we mainly focus on global equity at the allocation of natural resources, i.e., the governance of common-pool resources.

Equity, as defined by Oxford Language[5], is the quality of being fair and impartial. Equity focuses on allocating those resources and opportunities in a way that supports a goal of similar outcomes. Given its central importance, a lot of research has been done in this area. In the 1960s, the equity theory was first developed by J. Stacy Adams, which provided a structure and basic assumptions for further analysis[6]. Arun Agrawal made a critical assessment of the field of common properties and suggested two strategies[7]. Anthony C. Fisher studied the role discount plays in resource governance[8]. Francis N. Okpaleke studied the dynamics of resource governance specifically in Nigeria and Norway[9]. Many models have been established to measure the influence of policies, such as the ERC model put forward by Gary E Bolton[10].

In the unique content of asteroid mining, it's natural to introduce the relevant laws and regulations established by the UN, more specifically, the United Nations Office for Outer Space Affairs, The Property Rights in Outer Space, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, and Property Rights without Sovereignty, all of which are the basis of our model[11][12][13].

1.3 Problem Restatement

Firstly, we need to assign a definition to global equity in this specific area for further deduction. Due to the high cost of asteroid mining, we cannot consider the allocation of resources only in terms of needs. We have to consider the cost to build a more solid and practical definition of global equity.

Concomitantly, we need to make general assumptions to estimate the possible structure of future asteroid mining, including its costs, profits, revenue flow, and regulations. Based on the influences exerted by the asteroid mining industry, we need to analyze some representative nations' changes, to determine the industry's effect on global equity.

Then, we need to make horizontal comparisons to determine whether the governance of common-pool resources is in coordination with our definition of global equity, and vertical comparisons to justify our vision for the future of asteroid mining.

Lastly, we need to use the result of the comparison to determine what policies should be implemented to not only encourage the asteroid mining industry but also promote the advancement of global equity.

2. Assumptions and Justifications

Assumption 1: Asteroid mining is feasible and the safety issue is resolved and at a cost that is financially worth the investment;

Assumption 2: Asteroid mining has limitations, both in mining time and in mining rewards;

Assumption 3: The wars and economic sanctions are opt-out in our model, the international disputes are resolved by relatively mild approaches;

Assumption 4: An administration entity exists to allocate natural resources and relevant issues concerning asteroid mining;

Assumption 5: All countries expect a fair return or more for what they invest in asteroid mining;

Assumption 6: All countries make comparisons with other countries to determine what their equitable return should be;

Assumption 7: All countries who perceive themselves as being in an inequitable situation will seek to reduce the inequity either by distorting their investment and/or return in their minds, by directly altering investments and/or returns, or by negotiating with the administration entity we presumed to exist;

Assumption 8: Asteroid mining has a similar code of practice and business structure to the traditional mining industry;

Assumption 9: The motive function is continuous and second-order differentiable on the game payoff - relative share of the payoff plane;

3. Notations

Table 1

Symbol	Definition
$\boldsymbol{A_B^{1:K}}$	The set of all vectors of K decision-makers.
w^O	The overall optimal weight.
$\boldsymbol{W^k}$	The weight vector of the kth decision-maker.
α	The parameter determining the Dirichlet distribution.
α_p	The posterior parameter of the posterior distribution.
g_i	The gain of the game for player i.
m_i	The motivation function of player i.
s_i	The relative share of the payoff.
c	The total pecuniary payout.
$p(c, s_P)$	The probability that a random responder will reject the offer by P;
k	The size of the cake.
$\bar{k}$	The upper limit of the size of the cake.
$\underline{k}$	The lower limit of the size of the cake.
$p_u(g)$	The probability that g will be rejected by a random responder.

4. Global Equity Metrics

4.1 Global Equity Definition

To interpret the concept of global equity, we start by determining the properties of asteroid mining. According to *Assumption 2*, asteroid mining will not lead to unlimited resources' supply. We can thus identify the asteroid mining governance as a governance of the common-pool resources, such as deep-water resources, orbital shells, and atmosphere carbon emission.

The global in the "global equity" represents that the asteroid resources are owned and shared by all humankind. Moreover, the consequences also fall on all humankind, hence the crucial importance of regulation in multiple common-pool resources' exploitation. However, global equity is a general concept, it mainly indicates the fairness of resource distribution among countries. Yet there is no direct measurement of equity in preceding research. We decide to find the aspects that demonstrate a direct correlation with fairness to quantify the equity.

4.2 Global Equity Indicators

According to previous research, global equity is subject to the synergistic effect of both the functional ability and the development tendency of a social organization[9][7]. Thus, we use two main aspects to portray the global equity characteristic of a social organization: Resource Governance (RG) and Sustainability Impact (ST). Based on the results of several research and the criterion determined by the National Resource Govern Institute,[9][14] we can determine the indicators, which are shown in Figure 1.

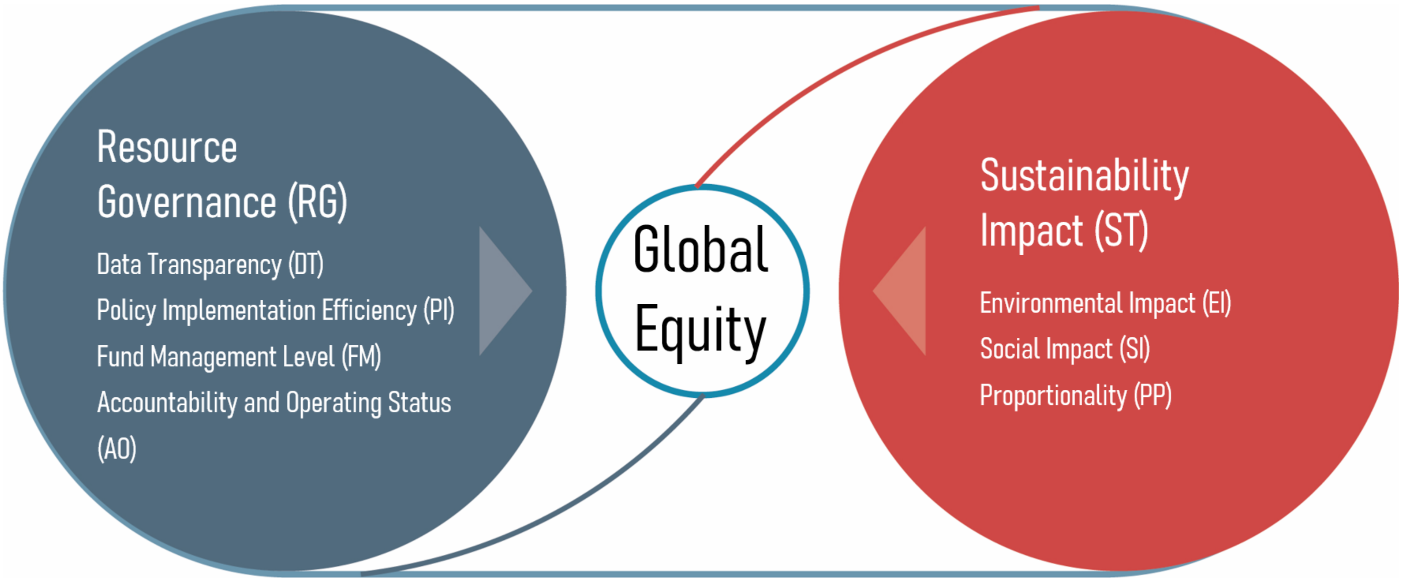

Figure 1. Indicators of Two Aspects

4.3 Global Equity Measured in The Traditional Mining Industry

Consider *Assumption 8*, we select the traditional mining industry as our historical analysis object.

In the traditional mining industry, value realization, revenue management, and enabling environment are put forward as the main aspects influencing global equity[15]. Accordingly, we selected the measurements that best represent those aspects and reformed them into our model. The indicators' interpretations and measurements for the traditional mining industry are shown in Table 2.

Table 2

Resource Governance (RG)	DT	The transparency of a social organization in its data.	Exposure rate of original data; Integrity of the published data;
	PI	The transformation gap between a policy and its implementation.	Gap duration time; Implementation intensity;
	FM	How well can a social organization manage its revenue.	Fund flow index; Asset management performance;
	AO	How reliable and energetic a social organization is.	Expected growth tendency; Key performance indicators;
Sustainability Impact (ST)	EI	The environmental impact a social organization exerts in function.	Pollution amount; Production waste treatment assessment;
	SI	The impact a social organization exerts on society.	Negative reviews; Social responsibility taken index; Propaganda intensity;
	PP	The occurrence of monopoly or dominance.	Market occupancy rate

Even though we cannot directly know the measurements of the future asteroid mining industry, we can still use the same indicators according to *Assumption 2*. Of note, the measurements of sustainability impact indicators may not be the same depending on the social organization we created in *Assumption 4* and the unique content of space. Specifically, we use the amount of space waste per unit cube of asteroid mining to measure the EI indicator, rate of mortality in asteroid mining per year measures the SI indicator. PP indicator is measured by the concentration ratio of the asteroid mining industry.

Thus, we have established the basis of the global equity metrics. More elaborated analyses using this metric are presented in the following models.

5. United Nations Space Resources Organization Model

5.1 Current Global Government of Common-Pool Resources

When considering the government of common-pool resources, satellite orbital shells' regulation garners the most attention. The frequency orbit resource is a limited, non-renewable common-pool resource, however, national regulators such as the FCC are assigning orbital shells to mega-constellations on a "finders-keepers" rule, which is a "variant of complete lawlessness", concomitantly leading to disastrous consequences including maldistribution, rent-seeking, and inefficiency[16]. This socially dysfunctional phenomenon is even more severe considering its content. The crowded orbit would and have led to unwanted collisions, producing fragments that are of a great security risk[17]. Hence the importance of a more strict and responsible organization in asteroid mining.

5.2 Establishment of UNSRO Model

UNSRO is short for United Nations Space Resources Organization, the administration entity we presumed in *Assumption 4*. Before we start to build the structure of UNSRO, we firstly determine the necessity for its existence. After we justified the necessity for the existence of UNSRO, we determine its purpose and principles, build its inner structure, and draw up its working procedure.

5.2.1 Justification of The Necessity of UNSRO's Existence

We made the existence of UNSRO an assumption at first, now we justify the necessity of its existence.

Let's put *Assumption 4* aside for the time being. Based on *Assumption 5, Assumption 6, Assumption 7*, all countries move forward in a non-zero-sum game. As is analyzed in the game theory, due to the differences in initial conditions, the gap among countries widens over time. When asteroid mining becomes possible, the situation becomes more like a dictator game[18]. Those who have the relevant technology can gain much more than the rest. The countries that don't possess the technology tolerate more according to *Assumption 7*. When the dispute constantly exists and widens, *Assumption 3* no longer holds, which leads to a contradiction. Thus, the necessity of the existence of UNSRO is justified.

5.2.2 Purpose and Principles of UNSRO

UNSRO is dedicated to promoting space resources' exploitation and utility while meeting the global equity metrics.

The three key principles are based on the regulations and laws revised by the United Nations Office for Outer Space Affairs. First and foremost, equity. Each country's gain is modulated to be in coordinate with its contribution; Secondly, efficiency. Minimize the bureaucracy and devote more resources to the actual work; Lastly, equality. Exert modulation so that the gap among countries won't drastically increase.

5.2.3 Structure of UNSRO

The member nations or organizations are categorized into two groups by the threshold of possessing the technology and equipment to perform asteroid mining. Those who meet the threshold are labeled A, and the rest are labeled B. (A-nations and B-nations for short) If due to special circumstances, some A-nations no longer possess the relevant technology or/and the equipment to perform asteroid mining, then they degrade to B-nations by the periodical assessment from the UNSRO qualification assessment department.

Except for the qualification assessment department, UNSRO has four else departments, which are the finance department, resource assessment department, human resource department, law and legislation department. The finance department is in charge of the revenue and expenditure of the whole asteroid mining process as well as the expenditure of maintaining the organization. The resource assessment department takes the responsibility to assess the availability and economically worth of a program. The human resource department supports the sound functionality of the UNSRO. The law and legislation department formulate the relevant procedures and draft legal documents.

Moreover, a general secretary is elected at first to manage each departments' work from a global perspective. The inner structure of UNSRO is depicted in Figure 2.

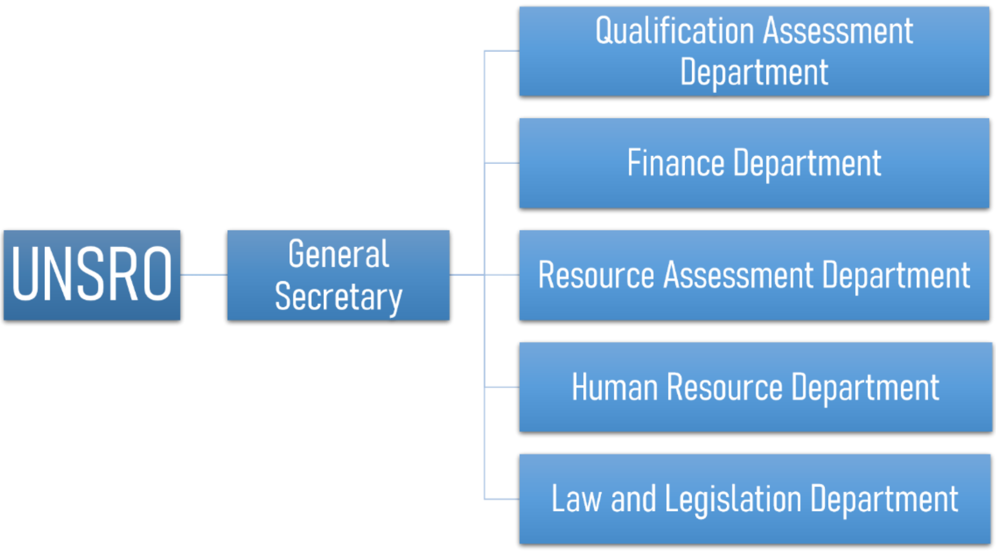

Figure 2. UNSRO Inner Structure

5.2.4 Working Procedure of UNSRO

The A-nations have the right to determine when to start an asteroid mining program. When at least one A-nation file a motion to start a mining program, the UNSRO would schedule a special session. The special session is composed of two parts:

Part 1: Firstly, the A-nations vote for the mining program. The session's procedure and the effectiveness of the voting result are based on the United Nations rules of procedure[19]. This voting is to determine whether to conduct this program. All representatives present come to an agreement on resource distribution among A-nations. If after the formal debate, the voting for agreement fails, the process goes back to the beginning. If the agreement passes, then we proceed to part 2.

Part 2: The B-nations bid for the rest of the resources at an initial price till none left. If there're left resources, then they are automatically divided by the top five countries with the most poverty validated by the World Monetary Organization.

Private organizations willing to contract asteroid mining program can file applications to the UNSRO. UNSRO has the responsibility to assess, revise, and determine the applications. The costs are on the private organizations and taxes are mandatory.

The flow chart of the above procedure is depicted in Figure 3.

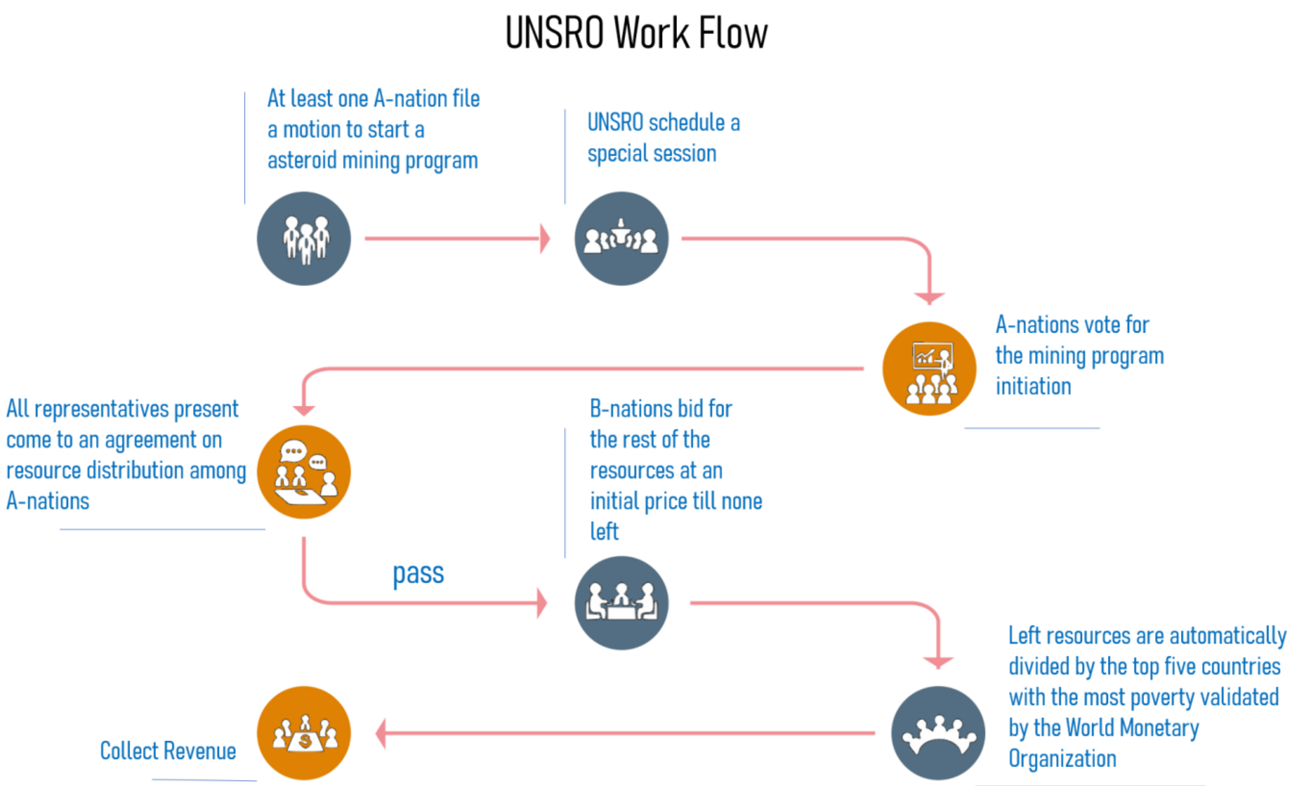

Figure 3. UNSRO Work Flow

5.2.5 UNSRO's Relationship with Other Entities

Through the procedure and structure discussed above, we can establish the relationships between other entities and UNSRO. The other international organizations are the collaborators of UNSRO. The nations and some private organizations are members as well as investors of UNSRO. Humankind is the service object of UNSRO. The exploration, object assessment, decision-making in asteroid mining is done as an interdepartmental achievement. The actual mining part, however, is done by the A-nations. The relationship is depicted in Figure 4.

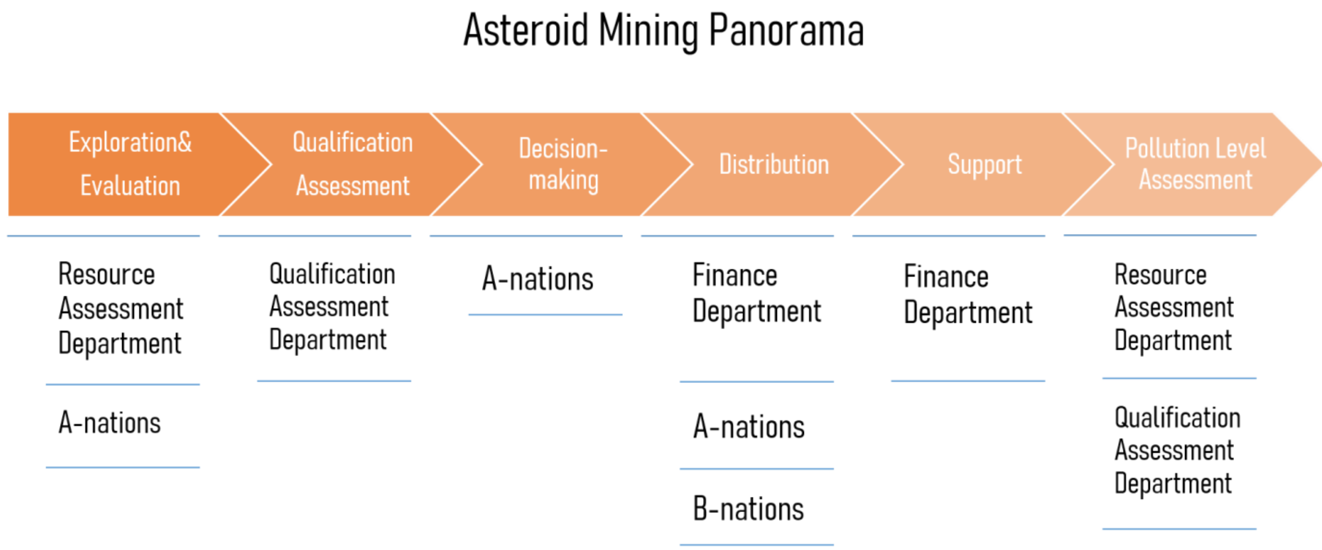

Figure 4. Asteroid Mining Panorama

6. Equity, Reciprocity, and Competition

6.1 Equity, Reciprocity, and Competition Model Establishment

The equity, reciprocity, and competition model aims to describe the different outcomes for different settings at the same initial state. The different settings are interpreted as the difference of in-game rules, based on the assumptions as of the initial state. The game theory is the model's major basis[10].

We concern ourselves with n-player games. In this game setting, all players are randomly selected, and anonymously matched. All game payoffs are monetary and nonnegative. Based on *Assumption 9*, we can therefore consider each game as a one-shot.

Each player acts to maximize the expected value of his or her motivation function

$$m_i = m_i(g_i, s_i) \tag{1}$$

in which[23]

$$s_i = s_i(g_i, c, n) = \begin{cases} g_i/c & \text{if } c > 0 \\ 1/n & \text{if } c = 0 \end{cases} \tag{2}$$

$$c = \sum_{j=1}^{n} g_j \tag{3}$$

We notice that

$$g_i \equiv c s_i(g_i, c, n) \tag{4}$$

Based on *Assumption 7*, we can deduce that

$$\begin{aligned} m_i^{(1)}(g_i, s_i) \geq 0 \\ m_i^{(2)}(g_i, s_i) \leq 0 \end{aligned} \tag{5}$$

Considering *Assumption 6*, when the pecuniary argument is held fixed, then the motivation function concaves in the relative argument, with a maximum around the allocation at which one's share is equal to the average share.

$$\begin{gathered} m_i(g_i, s_i) = 0 \\ \text{for } s_i(g_i, c, n) = \frac{1}{n}, m_i^{(2)}(g_i, s_i) < 0 \end{gathered} \tag{6}$$

To precisely describe the tension, we introduce two thresholds

$$r_i(c) = \arg\max_{\sigma_i} m_i(cs_i, s_i), c > 0 \tag{7}$$

$$m_i(ct_i, t_i) = m_i\left(\frac{0,1}{n}\right), c > 0, t_i \leq \frac{1}{n} \tag{8}$$

By analyzing the upper formulas, we find that for each c, there is a unique $t_i \in (0, \frac{1}{n}]$ and a $r_i \in [\frac{1}{n}, 1]$. We will also suppose that r_i is unique for each c.

We also make the following assumption to guarantee the heterogeneity: the inequality:

$$\begin{gathered} f^r(r \mid c) > 0, \quad r \in [1/n, 1] \\ f^t(t \mid c) > 0, \quad t \in (0, 1/n] \end{gathered} \tag{9}$$

holds for all $c > 0$.

Now, we have established the Equity, Reciprocity, and Competition Model. Further analysis abides by these approximations and assumptions.

6.2 ERC in Asteroid Mining Industry without UNSRO Regulation

The circumstances of the traditional mining industry are similar to a dictator game in the following setting: the dictator (D) distributes a cake of maximum size $k > 0$ between himself and a recipient. We represent the dictator's division as the pair (c, s_D) with $0 \leq c \leq k$. In this representation, the dictator's payoff is cs_i, and the recipient's payoff is $c - cs_i$.

Through mathematical analysis, we can come up with the following statement:

Statement 1: For all dictator's allocation, $c = k, s_D = r_D(c) \in [\frac{1}{2}, 1]$. Averagely, $\frac{1}{2} < \overline{s_D(c)} < 1$;

6.3 ERC in Asteroid Mining Industry with UNSRO Regulation

The most significant difference between asteroid mining and the traditional mining industry is that asteroid mining is regulated by only one entity from a macroscopic level yet traditional mining is regulated mostly by multiple separate entities like nations, companies, and international organizations. This largely simplifies our discussion. The members of UNSRO can be simplified as players in an ultimatum game described below.

Consider an ultimate between a proposer (P) and a responder (R). For the time being, we assume that the cake size, $k > 0$ always holds. We represent the proposal as (c, s_P), interpreted analogously to the dictator notation. To simplify the situation, we assume: if a responder is indifferent between accepting and rejecting, i.e., if $1 - s_P = t_R(c)$, the responder always accepts the proposal. We can establish the following statements:

Statement 2: For $c > 0$, $p(c, s_P)$ satisfies: $p(c, 0.5) = 0, p(c, 1) = 1$, p strictly increases in $s_P \in (0.5,1)$;

Statement 3: For all ultimatum proposals, $c = k, 0.5 \leq s_P \leq 1$;

Statement 4: On average, offers in the ultimatum game will be higher than offers in the dictator game, i.e., $\overline{s_D} > \overline{s_P}$;

From the statements, we can directly see that UNSRO regulation increases the distribution of gain, which also effectively inhibits the occurrence monopoly. Besides this, we can also conclude that the UNSRO regulation makes the asteroid mining industry more sustainable.

7. Bayesian Best-Worst Model

Now that we have established the detailed structure of the future asteroid mining industry. To further analyze and determine its impact on global equity, we select a weight calculation method called the Bayesian best-worst method to calculate the weight of the global equity metrics we defined. This method is developed based on a Bayesian hierarchical model and the best-worst method. The results obtained by the Bayesian BWM yield much more information in comparison to that of the original BWM according to current research[20]. We divide the model into two parts: data normalization and weight calculation.

7.1 Data Normalization

We use two vectors to represent the two aspects: $\boldsymbol{A^1}$ for Resource Governance and $\boldsymbol{A^2}$ for Sustainability Impact. The indicators are considered as the component of the vector. We label their indicators in numerical order as shown in Table 3. These indicators are the decision criteria.

Table 3

Indicator	DT	PI	FM	AO	EI	SI	PP
Notation	a_1^1	a_2^1	a_3^1	a_4^1	a_1^2	a_2^2	a_3^2

Now we select the best and the worst criteria from each vector, a_B^1, a_W^1 and a_B^2, a_W^2. Based on the decision makers' preference, the best criterion is the most important while the worst criterion is the least important among others.

After the best and the worst criteria are determined, we make a pairwise comparison between the best and other criteria from each vector to calibrate the preferences of all criteria. The calibration is based on ranking in the range from 1 to 9, increase in number represents the increase in importance. We obtain the "Partial Best" vectors:

$$\boldsymbol{A_B^1} = [a_{B1}^1, a_{B2}^1, a_{B3}^1, a_{B4}^1]$$
$$\boldsymbol{A_B^2} = [a_{B1}^2, a_{B2}^2, a_{B3}^2]$$

Where a_{Bj} represents the preference of the best to the criterion a_j.

Similarly, we can obtain the "Partial Worst" vectors $\boldsymbol{A_W^1}$ and $\boldsymbol{A_W^2}$. After the worst criterion is established, the comparisons are made to calibrate the criteria over the worst criterion by a number in the ranging from one to nine. The result is denoted as

$$\boldsymbol{A_W^1} = [a_{1W}^1, a_{2W}^1, a_{3W}^1, a_{4W}^1]$$
$$\boldsymbol{A_W^2} = [a_{1W}^2, a_{2W}^2, a_{3W}^3]$$

The following are the procedures in the mediocre best-worst method. We show the steps to make a comparison between the Bayesian best-worst method and the ordinary best-worst method.

Now we compute the optimal weight vector using the "Partial Best" and "Partial Worst" vectors.[21]

$$\begin{aligned} &\min_{\alpha,w} \alpha \\ &\text{s.t.} \left|\frac{w_B}{w_j} - a_{Bj}^k\right| \leq \alpha \quad \forall j = 1,2,\dots,n \\ &\left|\frac{w_j}{w_W} - a_{jW}^k\right| \leq \alpha \quad \forall j = 1,2,\dots,n \\ &\sum_{j=1}^{n} w_j = 1, w_j \geq 0 \quad \forall j = 1,2,\dots,n. \\ &k = 1,2 \end{aligned} \tag{10}$$

To verify that the calculated weights are reliable, we introduce the consistency ratio β and the consistency index κ to measure the veracity.[21]

$$\beta = \frac{\alpha}{\kappa} \tag{11}$$

where the consistency index is a fixed value per a_{BW}. The lower β is, the more consistent the comparison system possesses.

According to relevant research, the criteria can be interpreted as random events, and their weights are thus their occurrence probabilities[20]. Moreover, the multinomial distribution can meaningfully model the inputs to the BWM, which leads to the analysis using the Bayesian estimation method in the next section.

7.2 Bayesian Estimation

To meet the demands that the weights satisfy the non-negative property and sum-to-one property, we find an appropriate distribution: the Dirichlet distribution. Given a parameter $\alpha \in R^n$, the Dirichlet distribution of the weights w is defined as[22]

$$\mathrm{Dir}(w \mid \alpha) = \frac{1}{B(\alpha)} \prod_{j=1}^{n} w_j^{\alpha_j - 1} \tag{12}$$

Instead of using the maximum likelihood estimation, we consider the Bayesian idea of analysis, in which the Dirichlet distribution is prior to the multinomial distribution. The posterior distribution would also be Dirichlet with the posterior parameter. are a result, the values of w are shown in a Dirichlet distribution. We now verify that the mode of the posterior distribution can provide the exact maximum likelihood distribution by only considering the effect exerted by $\boldsymbol{A_W^k}$.

The mode of the posterior distribution $\mu \in R^n$ with the parameter α_p

$$\mu_j = \frac{\alpha_p - 1}{\sum_{i=1}^{n} \alpha_{p_i} - n} = \frac{1 + a_{jW} - 1}{\sum_{i=1}^{n} (a_{iW} + 1) - n} = \frac{a_{jW}}{\sum_{i=1}^{n} a_{iW}}, \forall j = 1, \dots, n \tag{13}$$

7.3 Weight Calculation by BWM

The optimal weights of a set of criteria are found within the best-worst framework. To apply the Bayesian estimation, we firstly identify the dependence among variables. From our calculation, we can identify that the $\boldsymbol{A_B^k}$ and $\boldsymbol{A_W^k}$ are independent. The value of $\boldsymbol{W^k}$ is dependent of $\boldsymbol{A_B^k}$ and $\boldsymbol{A_W^k}$, and the value of w^O is dependent on the value of $\boldsymbol{W^k}$. As depicted in Figure 5.

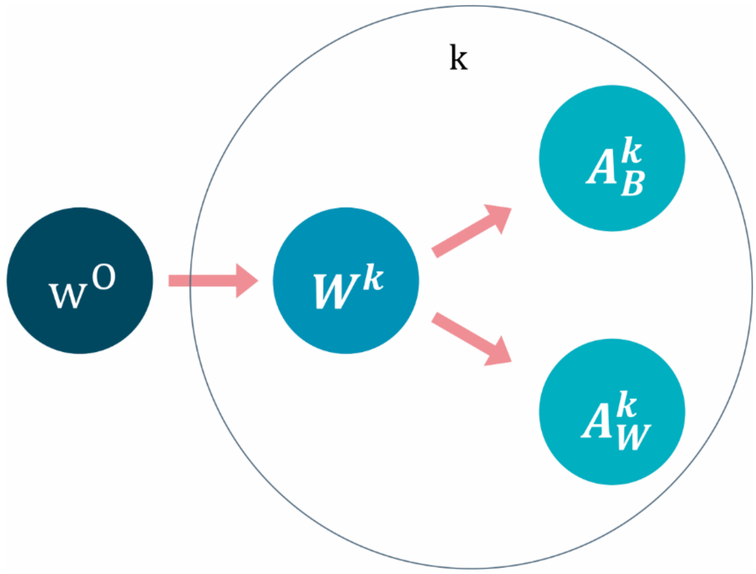

Figure 5. Relationship Among Variables

The joint probability distribution of all random variables is present below:

$$P\left(w^O, \boldsymbol{W^{1:K}} \mid \boldsymbol{A_B^{1:K}}, \boldsymbol{A_W^{1:K}}\right) \tag{14}$$

After this probability is calculated, the probability of any individual variable can be computed using the probability rule

$$P(a) = \sum_{b} P(a, b) \tag{15}$$

In which the letters represent two arbitrary random variables.

Considering the relationship among variables, combing the chain rule, we obtain

$$\begin{aligned} &P\left(w^O, \boldsymbol{W^{1:K}} \mid \boldsymbol{A_B^{1:K}}, \boldsymbol{A_W^{1:K}}\right) \propto P\left(\boldsymbol{A_B^{1:K}}, \boldsymbol{A_W^{1:K}} \mid w^O, \boldsymbol{W^{1:K}}\right) P\left(w^O, \boldsymbol{W^{1:K}}\right) \\ &= P(w^O) \prod_{k=1}^{K} P\left(\boldsymbol{A_W^k} \mid \boldsymbol{W^k}\right) P\left(\boldsymbol{A_B^k} \mid \boldsymbol{W^k}\right) P\left(\boldsymbol{W^k} \mid w^O\right) \end{aligned} \tag{16}$$

We now specify the distributions of each component in the upper equation. Since $\boldsymbol{A_B^k}$ and $\boldsymbol{A_W^k}$ can be perfectly modeled using the multinomial distribution[20], then we model them as

$$\boldsymbol{A_B^k} \mid \boldsymbol{W^k} \sim \text{ multinomial } (\frac{1}{\boldsymbol{W^k}}), \forall k = 1, \dots, K \tag{17}$$

$$\boldsymbol{A_W^k} \mid \boldsymbol{W^k} \sim \text{ multinomial } (\boldsymbol{W^k}), \forall k = 1, \dots, K \tag{18}$$

We change the Dirichlet distribution's parameters with its mean and a parameter that reflects the concentration. Given w^O as the mean of the distribution and δ as the concentration parameter[20], we can establish that

$$\boldsymbol{W^k} \mid w^O \sim \text{Dir}(\gamma \times w^O), \forall k = 1, \dots, K \tag{19}$$

$$\delta \sim gamma(a, b) \tag{20}$$

In which a and b form the shape of the gamma distribution. Now we supply the prior distribution over within a uniform Dirichlet distribution with $\alpha = 1$. Thus, we obtain

$$w^O \sim Dir(\alpha) \tag{21}$$

8. Policies in Favor

Based on the Bayesian best-worst method we have put up, we can now quantify the factors that affect global equity. We then proceed to analyze the traditional mining industry and the asteroid mining industry we presumed. The two industries are intimately linked.

8.1 Traditional Mining Industry Assessment

Since we cannot presume the specific data in the asteroid mining industry, doing which would be extremely inaccurate, we consider that the analysis of the traditional mining industry could lend deep insight into the study of the asteroid mining industry based on *Assumption 8*.

We choose Africa as our analysis object, for Africa is a major producer of many key mineral commodities and has the mining industry as one of the pillar industries[24]. A lot of research has been conducted and many policies, regulations are taking effect, which offers us a broad view of the whole industry.

We selected seven representative countries including the Democratic Republic of Congo, Ghana. Nigeria, Senegal, Tanzania, Tunisia, and Uganda. We apply the Bayesian best-worst method on the collected relevant data[14] to see how well do these countries perform in terms of our global equity metrics and how the weights distribute among indicators. The result we obtain is shown in Table 4.

Table 4

Aspect	RG				ST		
Indicator	DT	PI	FM	AO	EI	SI	PP
Weight	0.375423	0.201438	0.238611	0.184529	0.212172	0.326608	0.461220

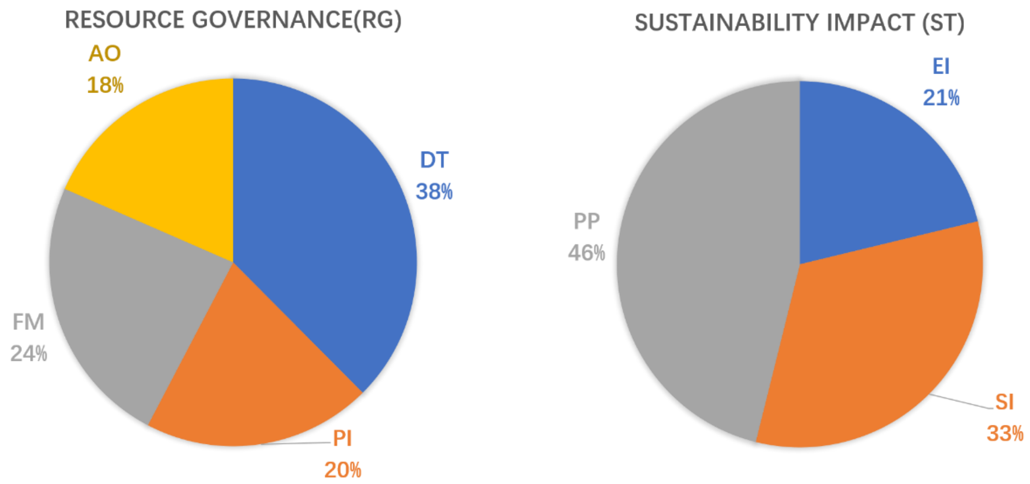

Figure 6. Weight of Each Indicator

From Figure 6 above, we can intuitively see that in the Resource Governance aspect, the DT indicator takes up the most weight, about 38%. The rest three indicators take up approximate weights, FM, PI, AO are arranged in a decreasing order. The result makes sense, for the transparency and integrety of data provided is the foundation of three other indicators. The lack of data or data fraud would otherwise lead to false estimation. Thus, data transparency should be guaranteed in the first place.

In the ST aspect, the PP indicator takes up the most weight, roughly 46%. The SI indicator takes up the second position. The EI indicator takes the least weight, about 21%, which can explain the reason why even though the environmental impact is crucial in industry sustainability, the relevant measurements are still neglected. Moreover, proportionality, as we have discussed, accounts for global equity as a major factor, which should be considered in the first place regarding policy establishment and implementation.

8.2 Asteroid Mining Policies in Favor

Based on the weight ranking obtained above, we make policies on the asteroid mining industry accordingly following the principle of higher weight priority, meanwhile considering the low weight indicators for comprehensiveness. The policies we suggest to be implemented to encourage the asteroid mining industry advancement in a way that promotes more global equity are as follow. Of note, the sequence here implies the degree of importance.

8.2.1 Policies in Resource Governance Aspect

1. Forced data disclosure in all entities involved;

As discussed above, the reliability and integrity of data are the pillar stone of the assessment model. Forcing data disclosure in all entities can contribute to UNSRO governance on outer space resources including asteroid resources. A more integrated and transparent industry prospect is formed.

2. UNSRO should conduct effective risk management to minimize the effect of uncertainty;

Effective risk management is a key element of fund management and will provide reasonable assurances on the risks. Significant risks should be identified and monitored, enabling more efficacious measurements. Moreover, risk management should be integrated into many mining program planning, and decision making, as is suggested in many guidelines and regulations[25]–[27].

3. The policy should be implemented after the assessment of Monitoring and Evaluation systems;

Policy implementation efficiency is obvious to all, failure of which can cause financial waste, political frustration, and disruption. In real world politics, policy coordination and the implementation of Monitoring and Evaluation systems are two practical ways[28]. The establishment of a Monitoring and Evaluation system should take place at the same pace as the establishment of UNSRO.

8.2.2 Policies in Sustainability Impact Aspect

1. The working procedure of UNSRO is strictly followed and each resolution is documented and reviewed to protect proportionality;

We have established a standard working procedure of UNSRO under the principle of safeguarding global equity across the asteroid mining industry. To protect proportionality, each resolution and working document should be documented and reviewed. In this way, we can spare no effort to avoid the occurrence of hegemonism as well as a monopoly, which could lead to devastating consequences.

2. The labor forces' safety, as well as mental health, should be fully considered and minimum treatment standards should be established and followed;

Due to the hazardous working conditions in outer space, the involved labor forces' safety and treatment should be taken into account. The treatment standards should be established under the relevant conventions, such as ILO Forced Labor Convention[29]. Eliminating the risk by formulating standard working procedures is of vital importance in the social impact of the asteroid mining industry.

3. All asteroid mining activities are conducted after the permission by authorities in UNSRO and reviewed to avoid pollution;

Although the environmental impact indicator takes up the least weight, it's still worthwhile to be addressed in policies. There may have certain means of asteroid mining that gains efficiency at the cost of pollution in outer space. Since all asteroid mining activities are arranged by UNSRO authorities, we consider that it would be more appropriate for UNSRO authorities to determine the mining plan and monitor the process. When the pollution level is beyound the acceptable range, the related mining unit would receive punishment.

9. Sensitivity Analysis

The sensitivity we analyze here is focused on the ERC model. From previous discussions, we know that the core idea of the ERC model is deducing statements using the assumptions we presumed under the given game setting that fits. The initial states are equal, the different game settings would lead to different statements. In chapter 7, we analyzed the difference of global equity in the asteroid mining industry with/without UNSRO regulation, concluded that UNSRO regulation increases the distribution of gain and the sustainability of the asteroid mining industry. To conduct the sensitivity analysis, we are dedicated to finding the difference in results under different game settings.

From the global equity metrics we established, we can choose one indicator to analyze its effect on the game setting. We make an assumption that the data transparency indicator of UNSRO shows low transparency. In terms of the game setting, the responder has to decide whether to accept or reject an offer of g monetary units without knowing the size k of the cake, however, knowing that the distribution of the cake satisfies a certain type of distribution, which we denote as $f(k)$, for it depends on the size of cake.

Within the domain $k \in [\underline{k}, \overline{k}]$, we suppose that $g < 0.5\underline{k}$. From previous research[30], we can confirm that the responders tend to reject g than if they know for sure that $k = \underline{k}$, and less likely to reject than if they know for sure that $k = \overline{k}$. We can make the following statement:

Statement 5: For all $g < 0.5\underline{k}$, $p\left(\underline{k}, \frac{\underline{k}-g}{\underline{k}}\right) < p_{\mathrm{u}}(g) < p\left(\bar{k}, \frac{\bar{k}-g}{\bar{k}}\right)$;

Statement 5 indicates that if data transparency is poor, the responders are more acceptable to inequitable distributions, which proves from another angle that data transparency is vital for global equity.

Of note, the model we use can only roughly determine the differences among settings. Under the circumstance that there is no actual data, the sensitivity can only be measured by this means. The stability can only be reflected by rough estimations.

10. Model Evaluation

10.1 Strengths

1. High Flexibility and Portability

The aspects and indicators are chosen dependent on the content of the mining industry. Moreover, the Bayesian best-worst model we established can determine indicators' weights in different situations. Indeed, we can apply this model to the interested study object and determine the weights of its indicators given the study object is influenced by multiple factors and data available. Namely, once the model is applied, the importance among different factors will be presented.

2. Precise Interpretability

The result from the ERC model reveals that our model performs well since it is consistent with phenomena in the real world. With the reasonable assumptions guaranteeing, the statements established by the ERC model can vindicate the positive effects on global equity exerted by UNSRO regulation.

3. Innovative Combination

Our Bayesian best-worst model built a connection between probability theory and group decision-making problems. The introduced Bayesian estimation innovatively offsets the inability of the best-worst method in preferences' amalgamation.

4. Validated Scientific Knowledge

The work we have finished is dependent on countless former researchers' contributions. Many of the assumptions made for the existence of UNSRO and the asteroid mining industry are based on validated scientific knowledge. Moreover, the inner structure and working procedure of UNSRO are established based on the United Nations and its departments.

10.2 Weaknesses

1. Accuracy Relies on Statistics

The analysis of the traditional mining industry applied the Bayesian best-worst model, in which most of the statistics reflecting the traditional mining industry are acquired from international organizations and companies. The accuracy of each indicator's weight using our model is dependent on the data.

2. Lack of Accuracy

We made assumptions to further simplify and normalize the problem. However, the assumptions we made may not reflect reality well, thus leading to a lack of accuracy. For instance, *Assumption 3* cannot even hold in current international status. When applying the models we established, this shortcoming has to be taken into consideration.

3. Lack of physical factor analysis

Considering the particularity of asteroid mining, many physical factors cannot be foreseen. And due to the lack of description of physical factors in the indicators, the model cannot effectively analyze these factors.

10.3 Generalizations

As we have discussed above, the management of the asteroid mining industry is essentially a common-pool resource distribution problem. Considering the growth in population and the decrease of disposable resources, our model can be adapted to many different application scenarios. For example, the distribution of satellite orbital shells and communication frequencies. Though ITU is involved in the allocation of frequencies to communications satellites, under whose binding instruments all countries must treat frequencies as limited resources, there's still massive perversion from private companies[24]. Likewise, the administration of deep-sea resources.

11. Conclusion

We analyzed the problems and identified the area the problems are related to. By reviewing previous works, we use the divide-and-conquer strategy to tackle each problem. We firstly established global equity metrics for clearer categorization and conciseness. Then, we selected seven factors as indicators for two main aspects of global equity based on former research. The resource governance aspect includes data transparency, policy implementation efficiency, fund management level, accountability, and operating status, the sustainability impact aspect includes environmental impact, social impact, proportionality. Accordingly, we selected indexes for measurement.

As for the possible scope of asteroid mining, we presumed the existence of an organization named the United Nations Space Resources Organization. Besides the justification of its existence, we established the purpose and principles of UNSRO, its inner hierarchy structure, working procedure, and relationships with other entities. Through the description and study of UNSRO, we reflected the regulations and development of the asteroid mining industry. The other international organizations are the collaborators of UNSRO, nations and some private organizations are members as well as investors of UNSRO. Humankind is the service object of UNSRO. The exploration, object assessment, decision-making in asteroid mining is done as an interdepartmental achievement. The actual mining part, however, is done by the A-nations according to our definition.

To determine the impact of asteroid mining on global equity, we developed the equity, reciprocity, and competition model using the established global equity metrics as indicators. By making reasonable assumptions and idealizing the real world restrains into mathematical expressions, we analyzed the difference between the asteroid mining industry with UNSRO regulation and the asteroid mining industry without UNSRO regulation and concluded that UNSRO regulation not only increases the distribution of gain but also conclude that the UNSRO regulation makes the asteroid mining industry more sustainable.

By analyzing the results concluded by changing the indicators, i.e., the sensitivity analysis of our equity, reciprocity, and competition model, we can see how the changes in the conditions affect global equity. We selected the data transparency indicator for demonstration and concluded that if data transparency is poor, the responders are more acceptable to inequitable distributions, which proves from another angle that data transparency is vital for global equity.

To determine the policies encouraging the asteroid mining industry while promoting global equity, we established the Bayesian best-worst model to assess the relative importance among indicators. Under the assumption that asteroid mining has a similar code of practice and business structure to the traditional mining industry, the relative importance of each indicator, i.e., the weight of each indicator, can be obtained by traditional mining industry assessment. Using the Bayesian best-worst model, we obtain the weight of each indicator. Concomitantly, we came up with policies with priority.

At the end of our paper, we made a sensitivity analysis, demonstrating that our model has stability under given assumptions and estimations. Further proved the correctness of the global equity metrics we established. In the following model evaluation, we concluded the strengths as well as weaknesses of our models and discussed some possible fields where our model may be applicable, such as satellite orbit shells' allocation and deep-sea resource distribution.

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