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F	MCM/ICM Summary Sheet	2218412

Global Equity and the Impact of Asteroid Mining

Summary

Exploring the universe is the eternal desire of human beings. With the rapid development of aerospace technology, the possibility of future asteroid mining is gradually recognized. While some hold a beautiful vision that large quantities of asteroid mineral resources will promote the development of both society and efficiency, others are worried that the potential social, political, and economical problems caused by asteroid mining will polarize global inequity.

We carefully define global equity and build a comprehensive measure of it. Since we assume global equity is related to the fulfillment of human needs, we choose 10 variables to cover different aspects, and preprocess data with **Multiple Linear Regressions** and normalization. Then we analyze their relationships with the five categories of **Maslow's Hierarchy of Needs** and use **Analytic Hierarchy Process (AHC)** to determine the weight of each variable. We use the model to calculate the **Fulfillment Score** for 193 countries. Borrowing the idea of **Gini Index**, we use a cumulative curve of Fulfillment Score to construct the **Global Equity Index (GEI)** and arrived at the GEI for 2021 is 0.1893. We explore why it is lower than the Gini Index, and validate our model through regional and historical analysis.

We project a vision for future asteroid mining industry with vivid specification. With solid research and reasonable assumptions, we propose the entire asteroid mining process as well as miscellaneous details about markets, funds, etc. We build the **Profit Models** to illustrate the economic activities involved in the process and conduct mathematical analysis regarding cost and profit. We discuss how asteroid mining may impact global equity in terms of the variables in our GEI model, and how the changes in asteroid mining conditions may influence global equity.

We suggest establishing Supervisory Mining Board, constructing Profit Distribution Scheme, launching International Research Collaboration Program, building Asteroid Mining Strategic Partnership, and prompting for Anti-Monopoly. Particularly, we have detailed the Profit Distribution Scheme using mathematical models. The profits will be divided into two parts—**Contribution Encouragement (CE)** and **Global Equity Fund (GEF)**. To encourage contribution, each entity in the asteroid mining sector would keep a proportion of profits for their own. Then, we use the **Entropy Weight Methods (EWM)** to objectively determine their extra reward for sharing technologies, platforms, resources, etc. We design a mechanism to distribute the GEF according to a formula derived based on GEI. We also discuss how to balance CE and GEF with consideration of efficiency-fairness trade-off, and apply an **Optimization Model** to provide suggestions.

Keywords: Analytic Hierarchy Process (AHP), Maslow's Hierarchy of Needs, Lorenz Curve, Global Equity Index (GEI), Profit Models, Entropy Weight Methods (EWM)

Contents

1 Introduction

1.1 Background

About ten billion years after the birth of the universe, a relatively stable ecosystem and social system have been built up by human beings and other creatures on earth. Tribes, ethnic or regional groups gradually developed into countries that spread across the globe. Nowadays, some countries are operating in a modern and highly developed mechanism while others suffer from high debts, poor environmental conditions, hunger, and even warfare.

According to *World Social Report 2020* issued by the United Nations, "the inequalities between less developed regions and countries and more-developed ones have hit a historical high." [1] The inequalities in resources have warranted the exploitation of the strong over the vulnerable, leading to even more serious inequity. Therefore, with the depression of more developed countries, less developed countries hardly have the chance to obtain the resources and the opportunities to develop themselves.

With a burning desire to solve such problems and achieve a more equitable society, our team decided to explore more possible solutions by focusing on the opportunities that outer space presents, which is asteroid mining. Asteroid mining has been seen as a great complement to human resources and a supply of resources to future in-space industrial activities. Moreover, our team notices its importance in redistributing the resources and giving human beings a chance to reverse this seemingly irreversible trend of inequity.

1.2 Our Work

In this paper, we complete the following work:

1. We build a comprehensive measure of global equity. We choose 10 indicators from different perspectives and analyze their relationship with the five **Maslow's Hierarchy of Needs** respectively. Then we use **Analytic Hierarchy Process (AHC)** to determine the weight of each variable and obtain a formula.

2. We collect the raw data for the 10 variables of 193 countries. Since there are many missing data, we use website search and **Multiple Linear Regressions** to add the data, and convert them into smoothed and normalized data. The result is used to calculate the corresponding Fulfillment Scores.

3. We borrow the idea from **Gini Index** and **Lorenz Curve**, and use a cumulative curve of Fulfillment Score to compute the **Global Equity Index (GEI)**. The GEI index for 2021 is 0.1893. We explored why it is lower than the Global Gini Index, and conduct regional and historical analysis.

4. We provide a vision for future asteroid mining. With solid research and reasonable assumptions, we propose potential scenes in the complete process from pre-mining planing, transition to the target asteroid, to production and transition back to earth and trading.

5. We build **Profit Models** for economic activities in the whole process. The overall cost is categorized into the early cost and ongoing cost, and they include research and development cost, exploration and prospecting cost, construction and infrastructure development cost, operational and engineering cost, transportation and shipping cost. Price fluctuation and its relation to mineral scarcity are taken into consideration. And we derive a profit formula.

6. We discuss the impact of asteroid mining on the global equity by measuring its impact on different indicators we choose. We assume the changes in asteroid mining and its subsequent influence on global equity.

7. To promote the global equity, we suggest asteroid mining be under the supervision of the United Nations, which will own the rights to distribute its profits. The overall profits will be divided into two parts—one for Contribution Encouragement and the other used for a **Global Equity Fund (GEF)**.

8. We suggest that for the Contribution Encouragement part, asteroid mining sectors will keep a proportion of profits for their own, and we use the **Entropy Weight Methods (EWM)** to objectively determine their reward for sharing technologies, platforms, and help. For the funding part, we establish a mechanism to distribute the fund according to our **Global Equity Index (GEI)**. We also discuss how to balance the two parts, considering an efficiency-fairness trade-off, and applied an **Optimization Model** to gain insights.

9. We propose some other policy recommendations for asteroid mining. We suggest regulation by multi-authorities, an **International Research Collaboration Program**, an **Asteroid Mining Strategic Partnership** and anti-monopoly anti-oligopoly policies.

10. We discuss the strengths and weaknesses of our models, and look to future improvements.

1.3 Assumptions

1. **Asteroid mining is profitable.**
   We assume that except in the early stage of scientific research, people conduct large-scale asteroid mining only when it is profitable. The total output value (or equivalent value) will surpass the total cost in asteroid mining. Then, we will have extra profit to be used as Global Equity Fund.

2. **The United Nations is an impartial institution.**
   We assume that the United Nations or the Supervision Committee is impartial. They will not favor any country, individual, or asteroid mining sector. The expert scoring for our contribution score is reasonable.

3. **Statistics for a country can represent the overall situation of a country.**
   We use the statistics for countries and do not consider the regional level. We assume they are enough to roughly measure the global equity.

4. **The data we collect is accurate.**
   Our data is collected from the World Bank Open data and some other official websites and research papers.

2 Global Equity Index Model

We define the global equity to be the distribution of fulfillment of different humankind needs across the world. People use different kinds of resources for their needs, all of which can be categorized into the five levels of Maslow's Hierarchy of Needs. Therefore, the level of fulfillment is a reasonable measure of using the resources that a country have to generate a certain amount of fulfillment/utility. We also refer to the definition of Gini Coefficient for the computation of the Global Equity Index.

We first select ten variables which are representative of humankind needs, and assign weights to each of the variable through the Analytic Hierarchy Process. Then, we are able to compute the Score of Fulfillment of people in countries through the model we have developed. After processing and normalizing data, we sort the score of fulfillment and compute the Global Equity Index.

2.1 Fulfillment Score

2.1.1 Variable Selection

To assess the level of fulfillment of people in a county, we choose factors in various aspects that are important to the humankind's fulfillment. The factors include the agricultural land, food production index, access to electricity, net national income, natural resources depletion, current health expenditure, unemployment, world happiness index, literacy rate, and research and development expenditure.

Table 1: Notations

Symbol	Definition
AL	Agricultural land: the index of arable land over total land area
FD	Food production: the amount of all crops and livestock products originating in the country
AE	Access to electricity: the index of population with access to electricity
NI	Net National income: the gross national income minus consumption of fixed capital and natural resources depletion
ND	Natural resources depletion: the sum of net forest depletion, energy depletion, and mineral depletion
HE	Health Expenditure: the expenditures on health
EM	Employment: the index of people employed over the total labor force in the country
HA	Happiness: the level of happiness the people in the country feel on average
EE	Expenditure on education: government expenditure on education
RD	Research and development expenditure: gross domestic expenditures on research and development

2.1.2 Data Preprocessing

The World Bank Open Data is an authoritative and comprehensive data source. It provides 5,121 types of statistics of the 193 member states of the United Nations.[2] Our data indicating people's fulfillment are mostly from the World Bank, except that the happiness score is from the World Happiness Report. [3]

We have relatively complete data for most of our 10 indicators of Fulfillment, but there are still a lot of missing data. We first conduct an Internet search, find some relative reports and manually add some data. Then, for some specific missing data in one country, we choose the relevant variables from the same country as predictors, and conduct a Multiple Linear Regression with the help of SPSS. The R^2's of most our regressions are larger than 0.6, indicating an acceptable consistency.

No matter how we adjust the predictors, the R^2 for research and development expenditure is too low. We find that many countries miss the data for research and development expenditure, and research in most of these countries is not taken seriously and not reported. We assume that they have a relatively low research and development expenditure, and use 80% of the regression output as their values.

The value of our features include percentages, small numbers of index, and big numbers, and thus they have very different scales. Before calculating the Fulfillment Score, we need to make sure that the features that are on a similar scale to prevent one feature from overly influencing the output. We first normalized data x_j for each variable j using the formula below:

$$x_j^{(i)} = \frac{x_j^{(i)} - ave(x_j)}{STD(x_j)} \tag{1}$$

where $ave(x_j)$ is the average value, and $STD(x_j)$ is the standard deviation.

2.1.3 Maslow's Hierarchy of Needs and Analytic Hierarchy Process

Maslow created a classification system which reflected the universal needs of society as its base and then proceeding to more acquired emotions [4]. We can consider the relationship between each of our ten variables and the five categories of Maslow's Hierarchy of Needs into two separate levels.

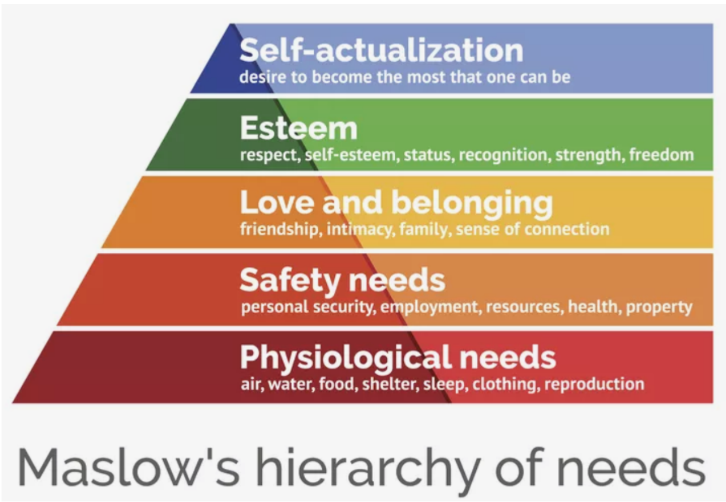

Figure 1: Maslow's Hierarchy of Needs

Then we use the Analytic Hierarchy Process [5] to determine the weight of each variable in the final calculation of the Score of Fulfillment. First, we set the ten variables and the five categories of Maslow's Hierarchy of Needs into two separate levels.

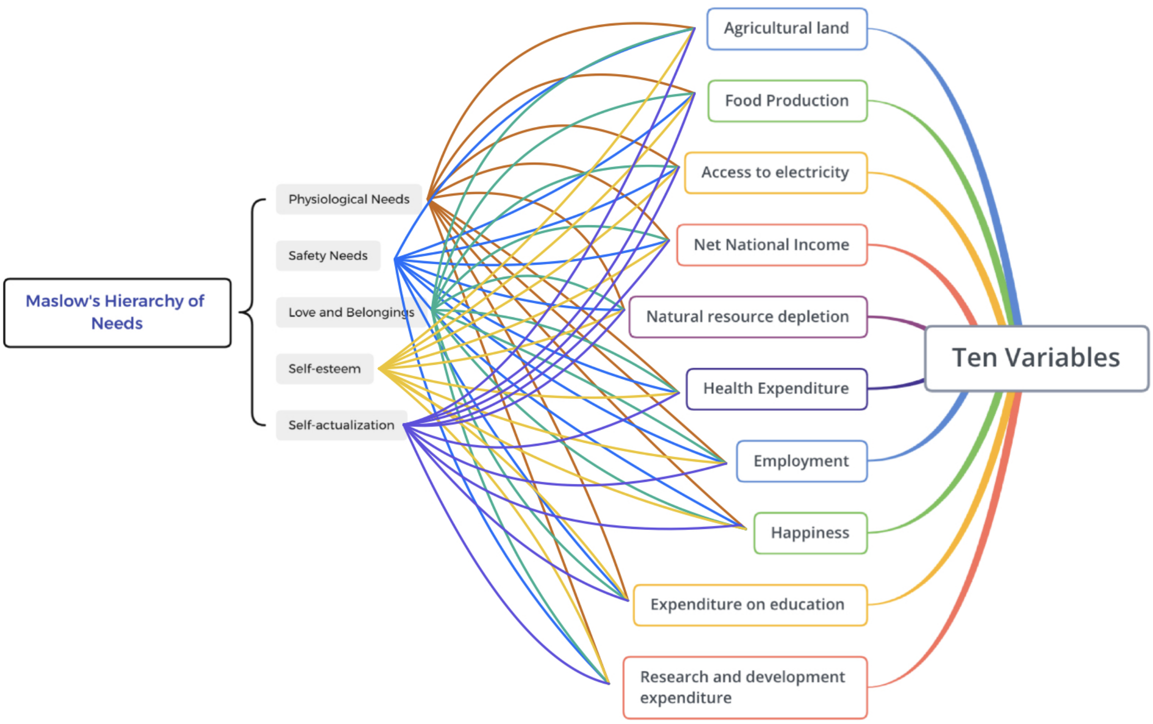

Figure 2: Analytic Hierarchy Process

Then, we establish the numeric value to represent scale of importance of one factor over another from 0 to 9, as shown in table below.

	Physiological Needs	Safety Needs	Love and Belonging Needs	Self-esteem	Self-actualization
Physiological Needs	1	3	5	7	8
Safety Needs	1/3	1	2	4	6
Love and Belonging Needs	1/5	1/2	1	5	8
Self-esteem	1/7	1/4	1/5	1	3
Self-actuallization	1/8	1/6	1/8	1/3	1

In the pairwise comparison matrix, the a_{ij} element represents the importance comparison of the ith factor compared to the jth factor. For instance, in the matrix below, the a_{12} element, namely 3, denotes that compared to safety needs, physiological needs is slightly more important.

For the pairwise comparison matrix, we compute the eigenvalue $\lambda = 5.3297$ and obtain an Consistent Index (CI) of 0.1014, which passes the consistency check 1.12. We repeated the steps above to compare the importance contribution of the ten variables to the five categories of Maslow's Hierarchy of Needs. Finally, through all the steps of Analytic Hierarchy Process, we computed the weight of each variable shown in the following figure.

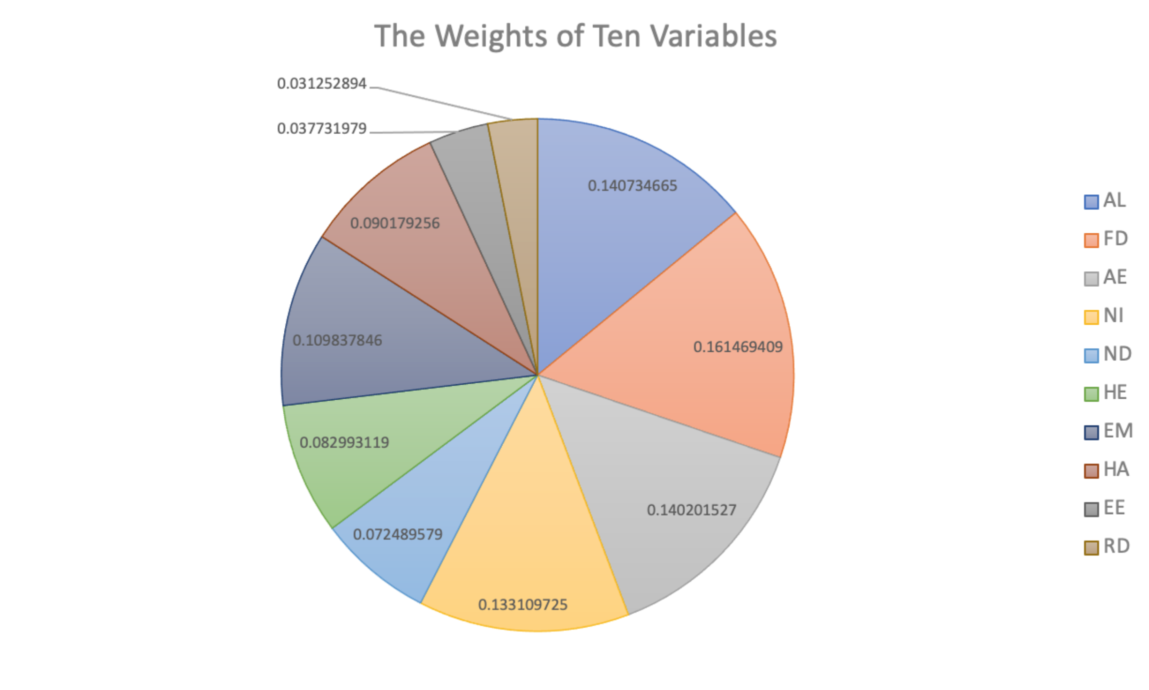

Figure 3: The Weights of Ten Variables

2.1.4 Fulfillment Score

After prepossessing the data and obtaining the scores s_i and weights w_i from the Analytic Hierarchy Process, we can calculate the Raw Fulfillment Score F_R. For each country,

$$F_R = \sum_{i=1}^{10} s_i \times w_i \tag{2}$$

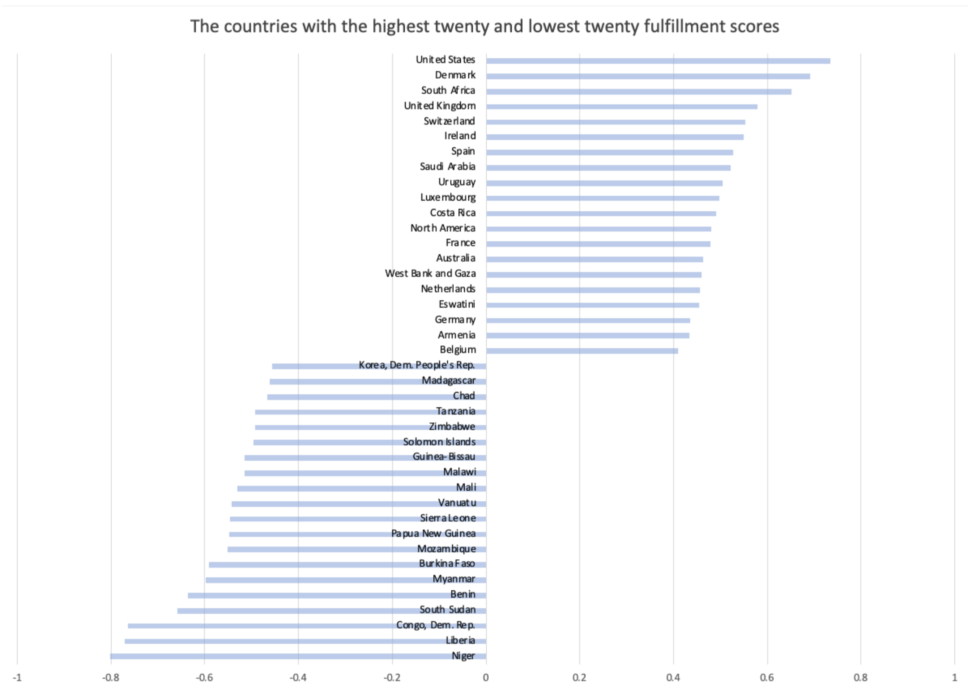

Figure 4: Raw Fulfillment Scores

We notice that some countries have positive Raw Fulfillment Score while others have negative ones. The maximum value is 0.7341 from the United States. The minimum value is −0.8014 from Niger. For the convenience of further calculation of Global Equity Index (GEI), we convert them into values in the range $[0,1]$, so we use the min/max normalization to obtain the Fulfillment Score F for our dataset D:

$$F = \frac{F_R - min_{F_R \in D}(F_R)}{max_{F_R \in D}(F_R) - min_{F_R \in D}(F_R)}. \tag{3}$$

2.1.5 Interpretation of the Fulfillment Score

We derive a Fulfillment Score for each country, which shows the level of people's relative fulfillment of needs in different aspects. Since people's needs and wants are unlimited, there is no such a full score to denote needs are all fulfilled. Therefore, we choose to set the score as a relative score compared to the most fulfilled country. That is to say, the country where people's needs are most fulfilled has a Fulfillment Score of 1, and the country where people's needs are least fulfilled has a Fulfillment Score of 0. The more needs are fulfilled, the higher the Fulfillment Score will be.

2.2 Global Equity Index

2.2.1 Connection with Fulfillment Score

Previously, we have defined the global equity to be the distribution of fulfillment of different humankind needs across the world. People are living in various ways but toward the same goal—fulfilling their needs and wants. Governments and countries operate for a similar purpose. Therefore, it is reasonable that the extent to which a country fulfill their people's needs is equivalent to the ability to acquire resources and fulfill needs at a certain efficiency. If all countries are equal, they should all have the same efficiency to acquire resources and fulfill their needs, no matter how big or small the countries are. Hence, Fulfillment Score is a valid measure for global equity.

2.2.2 Gini Index and Global Equity Index

To build our Global Equity Index, we employ a similar idea with the Gini Index. In the graphical representation of Gini index, the smaller the area between the line of equality and Lorenz Curve, the more equality is achieved. In the Global Equity Index, we can draw a similar line of equity, which represents all countries all have the same efficiency to acquire resources and fulfill their needs. Similar to the Lorenz Curve, we have the curve of Fulfillment Score distribution, which is the cumulative distribution of Fulfillment Scores sorted from smallest to the largest.

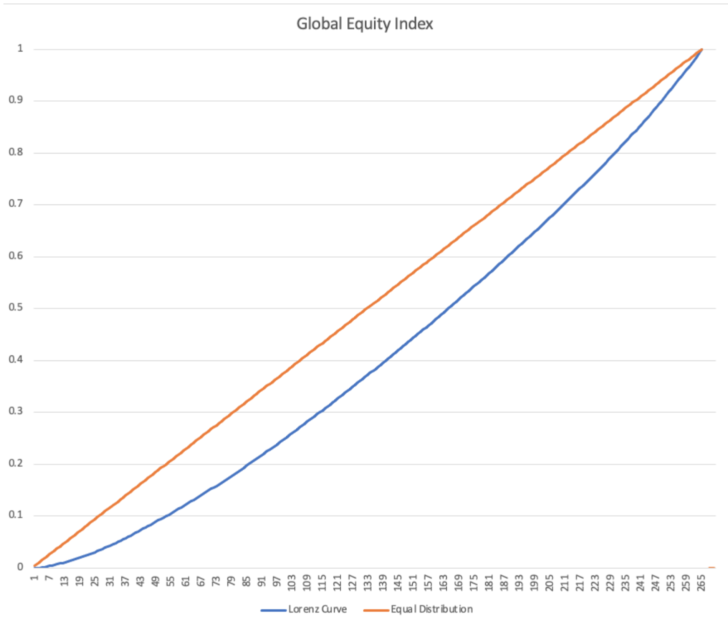

Figure 5: Global Equity Index

We calculate the Global Equity Index (GEI) with the formula below:

$$GEI = \frac{A}{A+B} \tag{4}$$

where A is the area below the Equal Distribution line and above the cumulative Fulfillment Score distribution curve, and B is the area below the cumulative Fulfillment Score distribution curve.

A Global Equity Index of 0 expresses perfect equality, where all Fulfillment Scores from different countries are the same. A Global Equity Index of 1 (or 100%) expresses maximal inequality among values (i.e. when only one country has an extremely high Fulfillment Score, and all others have extremely low ones, the Global Equity Index coefficient will be nearly one).

The result of our calculation shows that the Global Equity Index is 0.1893. It is relatively low compared to the global Gini Index (estimated to be between 0.61 and 0.68). However, the Global Equity Index is a comprehensive index combining 10 different variables, which makes a relatively large value unlikely to happen. We observe that if we calculate one index for each of the 10 variables in the similar way, all of them would be larger than our overall Global Equity Index. The strength of our Global Equity Index is that it is more comprehensive and take all five levels of Maslow's Hierarchy of Needs into account, each with reasonable weights.

2.3 Regional and Historical Analysis

To validate our model as well as gain valuable insights, we will analyze the global equity indexes we obtain from the model on a regional and historical perspective.

2.3.1 Regional Analysis

We color the map based on the fulfillment scores of different countries as shown below:

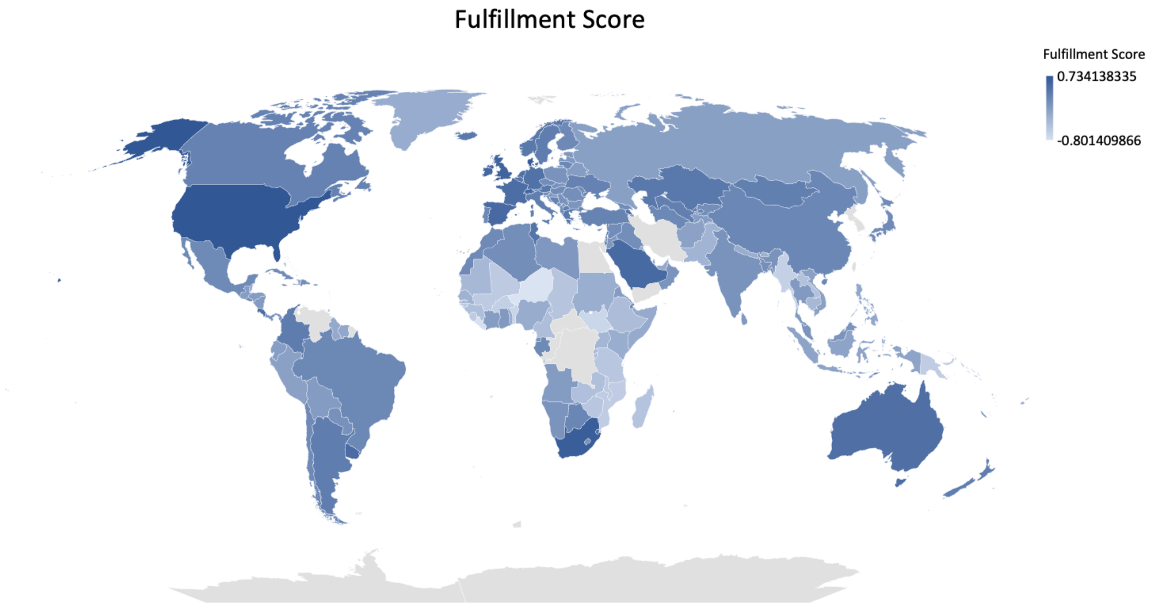

Figure 6: Fulfillment Score

The darker the blue color is, the higher fulfillment score the country or region has. From the graph, we can see the countries such as the United States, South Africa, and Australia have relatively high fulfillment scores while countries like Niger, Liberia, and Congo have relatively low fulfilment scores.

The visualization on the graph directly reflects the fulfillment of Maslow's five hierarchy needs are satisfied in a different level in different countries and regions, which fit into the reality. The countries like the United States have had the privilege over other countries due to its high national income per capita and advanced research and development. The figure below has shown forty countries with the highest twenty fulfillment scores and lowest twenty fulfillment scores.

2.3.2 Historical Analysis

We collect historical data of some variables from the previous years (2016-2018) if they are available. Using the same model, we derive a historical Global Equity Index (GEI) of 0.1872. It is sightly lower than 0.1893, the Global Equity Index (GEI) for 2021. We draw the conclusion that the Global equity has deteriorated in the recent five years.

3 Vision for Future Asteroid Mining

3.1 Vision for Different Stages of Asteroid Mining

In the future, the asteroid mining industry would be operated at a reasonable cost and returning rate under the supervision of the United Nations (UN) and specific bureaus in each country. Only a fraction of countries have the ability to conduct asteroid mining. The future asteroid mining industry would include the following stages: (i) Pre-Mining Planning; (ii) Transition to the Target Asteroid; (iii) Production and Transition Back to the Earth; and (iv) Trading.[6]

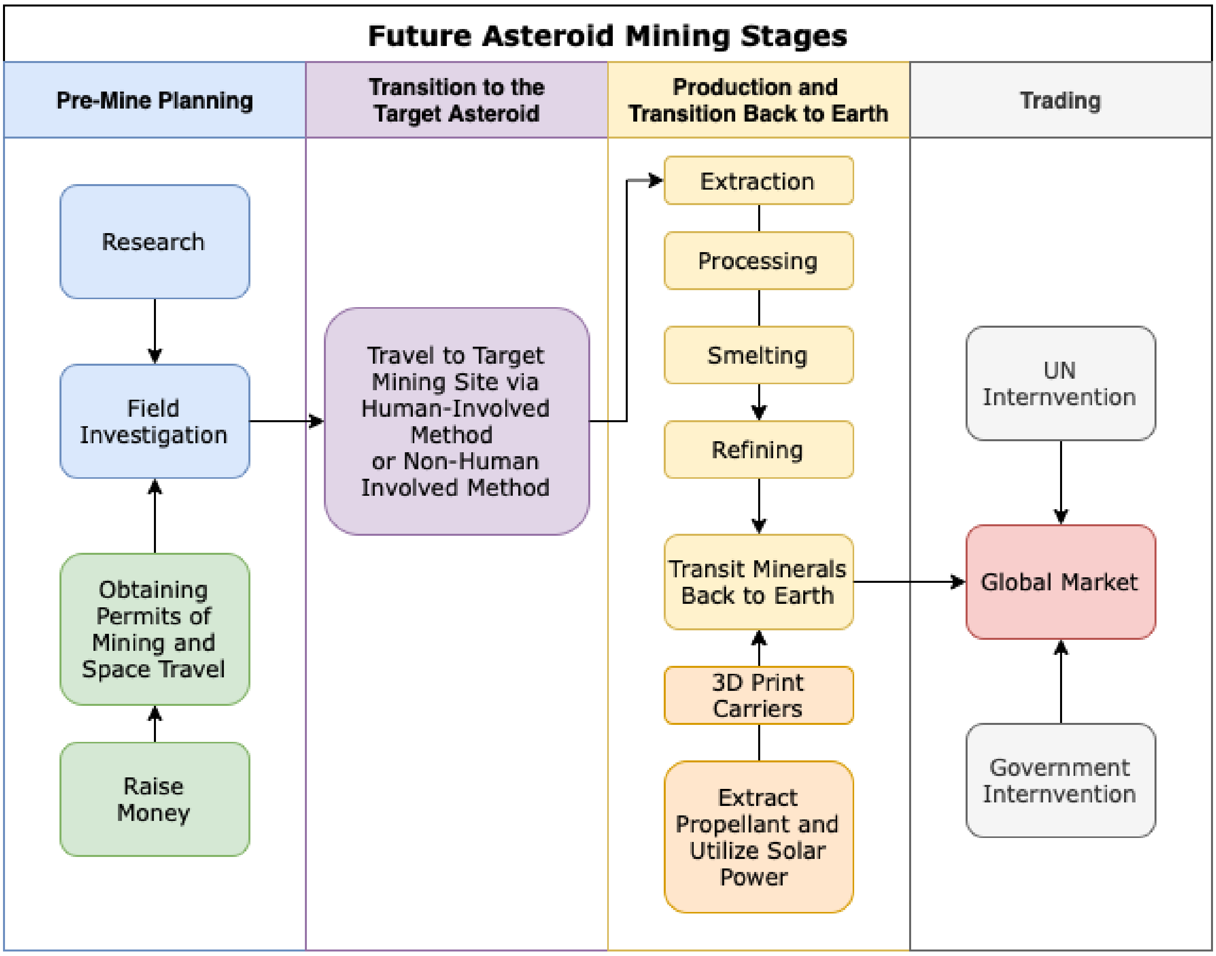

Figure 7: Future Asteroid Mining Stages

3.1.1 Pre-Mining Planning

Pre-mining Planning stage involves research, field investigation, obtaining permits, raising money for mining projects. On earth, researchers would first research about potential asteroids to be mined. Then, they would send drones, robots, or specialists to the asteroids to conduct field investigation if needed. Both public mining (mining by the government) and private mining (mining by private firms) exist. No matter what forms they are operating in, they will need to obtain permits including but not limited to the license to mine in asteroids in general, permit to mine the target asteroid, visa for leaving the earth (if any human staffs are involved). They are for the purpose of maintaining a safe asteroid mining environment, keeping record of asteroids to be mined, and gathering information for government decisions. The major two types of mining projects funding will be public funding and private funding. National public mining projects and international public collaboration projects fall under the category of public funding, which is to use government budget coming from tax. Private funding would mainly be the method of private firms, raising money from bank loans and investments.[7]

3.1.2 Transition to the Target Asteroid

There would be two types of transitions: human-involved and non human-involved. As it is costly to bring human to the space, the most transitions would be in the form of non human-involved. Public mining departments or private firms would send out spacecrafts from the spaceports built by the government, similar do airplanes leaving airports.

3.1.3 Production and Transition Back to the Earth

Due to the reason mentioned previously, the mining and production process would mostly be done by automatic robots in the asteroid or space. Materials that are generally to be mined include precious metals, ice, and so on. The mining and production equipment will extract, process, smelt, and refine the metals. The equipment would also be able to 3D print carriers to bring the minerals back to the earth at a relatively low cost by utilizing solar power and extracting propellant from the asteroid.

3.1.4 Trading

The minerals from the asteroid will be traded openly in a global market. The market is mostly free, meaning that the supply and demand would determine the price and quantity being sold, but at the same time, UN and governments could intervene the market to achieve certain goals. In the future, the price of the mineral would even lower than the price now, since a considerable amount would be supplied at a high efficiency. [8]

3.2 Model for Potential Costs and Source of Profit

This model conducts the economic analysis of the asteroid mining. It examines the cost and price of different processes in the asteroid mining and suggests the potential profits. It is related to the part that discusses how different asteroid mining sectors work, and lay a foundation for the profit distribution. It includes two parts—cost analysis and profit analysis.

The follow table lists the notations of this model:

Symbol	Definition
P_T	Total Profit
V_T	Total output value
V_U	Unit output value
C_T	Total cost
C_U	Unit cost
C_E	Early cost
C_O	Ongoing cost
$C_{RD}^{(e)}$	Research and development cost (early stage)
C_{EP}	Exploration and prospecting cost
$C_{RD}^{(s)}$	Research and development cost (subsequent stage)
C_{CI}	Construction and infrastructure development cost
C_{OE}	Operational and engineering cost
C_{TS}	Transportation and shipping cost

3.2.1 Cost Analysis

The Early Cost C_E is the fixed cost of asteroid mining. It includes two parts: Research and Development Cost in the early stage $C_{RD}^{(e)}$ and Exploration and Prospecting Cost C_{EP}. Both of them need considerable early investment and make future asteroid mining possible. As they do not provide direct benefits, we category them into the Early Cost. Thus the formula for the

Early Cost is as follows:

$$C_E = C_{RD}^{(e)} + C_{EP} \tag{5}$$

The Ongoing Cost C_O includes four parts: Research and Development Cost in the subsequent stage $C_{RD}^{(s)}$, Construction and Infrastructure development Cost C_{CI}, Operational and Engineering Cost C_{OE}, and Transportation and Shipping Cost C_{TS}. They are in the ongoing process of asteroid mining. Note that Research and Development Cost are divided into two parts—early stage $C_{RD}^{(e)}$ and subsequent stage $C_{RD}^{(s)}$—because research and development are essential throughout the whole process. Thus the formula for Ongoing Cost is as follows:

$$C_O = C_{RD}^{(s)} + C_{CI} + C_{OE} + C_{TS} \tag{6}$$

Note that the Ongoing Cost C_O increases in the process of mining and shipping back more minerals. For simplicity, let's define a "unit quantity" of minerals. It could be a specific type of mineral, or many different types of minerals, as long as each unit quantity of minerals require the same amount of the Ongoing Cost at a specific time.

The Total Cost C_T is a combination of Early Cost C_E and Ongoing Cost C_O.

$$\begin{aligned} C_T &= C_E + C_O \cdot Q \\ &= C_{RD}^{(e)} + C_{EP} + (C_{RD}^{(s)} + C_{CI} + C_{OE} + C_{TS}) \cdot Q \end{aligned} \tag{7}$$

And we can also derive the Unit Cost C_U.

$$C_U = \frac{C_T}{Q} = \frac{C_E}{Q} + C_O \tag{8}$$

3.2.2 Profit Analysis

Following the same idea, we define the Unit Value V_U. Since the asteroid minerals we hold to ship back are generally scarce and valuable, e.g. gold, platinum, palladium, their values are more or less depends on their scarcity. The more minerals people ship back or plan to ship back, the less scarce it would be on the earth, and the smaller it value would be. We assume the relationship is linear:

$$V_U = w_0 - w_1 \cdot Q \quad (w_0, w_1 > 0) \tag{9}$$

where w_0 is the initial value, and w_1 is elasticity between the unit mineral value and its quantity.

The Total Value V_U of minerals depends on the Unit Value V_U and the Quantity Q.

$$\begin{aligned} V_T &= (w_0 - w_1 \cdot Q) \cdot Q \\ &= w_0 \cdot Q - w_1 \cdot Q^2 \end{aligned} \tag{10}$$

With the Total Value V_U and the Total Cost C_T, we can derive the Total Profit P_T.

$$\begin{aligned} P_T(Q) &= V_T - C_T \\ &= (w_0 \cdot Q - w_1 \cdot Q^2) - (C_E + C_O \cdot Q) \\ &= -w_1 \cdot Q^2 + (w_0 - C_O) \cdot Q - C_E \end{aligned} \tag{11}$$

We can see when quantity is zero, the total profit is $P_{T(Q=0)} = -C_E$, which is exactly the early cost. If $C_O \leq w_0$, which implies that the ongoing cost is greater than the initial unit price of the mineral, the asteroid mining process will be not economically worthwhile. If $C_O < w_0$, which implies that the ongoing cost is smaller than the initial unit price of the mineral, the profit increases when the quantity starts to increase from zero. The profit would reaches its maximum value

$$P_{T,max} = \frac{(w_0 - C_O)^2}{w1} - c_E \qquad when \quad Q_{max} = \frac{w_0 - C_O}{w_1}. \tag{12}$$

Note that the maximum profit above may not be achieved for various reasons. The most likely one is the limitation of mining capacity. Another reason is the limitation on asteroid mining for the purpose of sustainable development. However, the formula for profit is more useful in general situations.

4 Asteroid Mining Industry and Global Equity

4.1 The Impact of Asteroid Mining on Global Equity

The asteroid mining activity will affect the net national income, natural resources depletion, employment, and research and development variables in the Global Equity Index Model above. GEI may increase as employment and research and development components widen the gap between countries, but GEI may not change significantly, since asteroid mining will benefit the net national income and natural resources depletion of the whole society at the same time, as long as the output is reasonably distributed.

4.1.1 Net National Income

The net national income will increase for most countries. Asteroid mining would be a mature industry at the time, so countries that have the ability to conduct asteroid mining would directly gain income from the industry; countries that do not have the ability can benefit from importing the minerals at lower prices. Since the net national income will increase for most countries, GEI may not be largely impacted.

4.1.2 Natural Resources Depletion

Outsourcing minerals will slow down the overall natural resources depletion on earth. The price of minerals coming from asteroids would be the same or even lower than those from the earth, so demand for minerals on earth would decrease, slowing down the depletion of natural resources. However, it is a global effect such that most countries will have the variable decreased, not resulting in a significant change in GEI.

4.1.3 Employment

Asteroid mining will create more jobs mainly in private mining firms, and national mining and spacing traveling bureaus. Such jobs require exceptional skills in technology, management, trading, or proficiency in geology and astronomy. Unfortunately, workers with few skills that used to work in basic positions like miners may be at the risk of unemployment, since their jobs will be replaced by machines. Countries with high Fulfillment Scores, usually more developed countries, would tend to have more new job opportunities in the asteroid mining industry, while countries with lower Fulfillment Score would be subject to workers losing jobs. The employment may not necessarily polarize the global equity problem, since the asteroid mining industry will stimulate the development of other related industries like equipment manufacture. Therefore, it is not clear how asteroid mining would impact Global Equity.

4.1.4 Research and Development

Research is a necessary part of the pre-mining stage, the research and development component in the Fulfillment Score would certainly increase for countries that are able to conduct asteroid mining, whereas countries that do not perform the activity will not benefit from it. Hence, there will be greater gaps between countries, resulting in a higher GEI.

4.2 Changes in Asteroid Mining and Their Subsequent Influence on Global Equity

4.2.1 Cost and Mining Opportunities

There are various costs comprised of the total cost. If the total cost is lower, more firms and countries would be willing to enter the market. As technology advances and the industry develops to operate on a large scale, the costs for construction, transition, and production will decrease. The costs incurred in the pre-mining stage, namely, research and development cost and exploration and prospecting cost would hinder many developing countries to step into this industry. Therefore, if the costs during the pre-mining stage are significantly reduced by means like funds, technology sharing, and international collaboration, then asteroid mining would be more accessible for developing countries that previously do not have the ability to conduct such activities. Net income and natural resources depletion would be affected, and hence GEI would decrease.

4.2.2 Jobs

Since the asteroid mining is a new industry, the capital-intensive investment will not create a large amount of job vacancy and correspondingly solve the problem of seasonal cyclical unemployment due to the depression of economics. In addition, the demand for labor force mainly points to the high-tech talents from each country, making the demand for high quality labor increases while the demand for regular labor force might not increase. Namely, the countries will invest more money on high standard education such as college education while the mainstream labor force will only encounter a modest increase of demand in this industry.

4.2.3 Market

The market for asteroid mineral trading is visioned to be an openly-trading and mostly free market with UN and government interventions sometimes. If the market is oligopoly, meaning that a few countries and firms are the only oligarchs on the supply side of the market, the price of the asteroid minerals would be rigid, and may thus be inaccessible to countries that want the resources but have limited ability to way, and thus widening gap in the net national income, resulting in a higher GEI. If the market is frequently intervened by UN and governments, lower GEI may be achieved, since the net national income and natural resources depletion will be more uniformly distributed. However, the society is not operating at high efficiency, incurring some social loss.

5 Policy Recommendations

Asteroid mining is an attractive future project with many possibilities in resources and profits for many developed countries and private businesses that have ambitions to expand their technological regime and enhance international positions. However, a market without appropriate supervision will finally lose control and lead to chaos in society. Therefore, it is necessary to establish a regulated market and intervene through aids and subsidies to prevent potential social and political problems as well as to encourage the development of the asteroid mining industry. More importantly, the immature asteroid mining industry should be carefully planned such that developing countries will have access to the resources, leading to a more equitable society.

5.1 Supervisory Board

The asteroid mining project involves not only economic benefits but also political and social issues due to its potential gigantic economic and social values, so the immature asteroid mining market needs the supervision of authorities.[9] Since asteroid mining is an interplanetary activity, the benefits of all humankind should considered as a whole. Therefore, it is necessary to establish supervisory board on both global scale and national scale. The global mining board, potentially falls under UN, should be in charge of balancing and redistributing the benefits of asteroid mining, as well as connecting countries to facilitate international collaboration. To achieve it, the global mining board can establish a Profit Distribution Scheme which is specified in the following section. National mining boards should carefully plan and regulate their asteroid mining industry according to their countries' characteristics. The national mining boards should also collaborate with the global mining board.

5.2 Profit Distribution Scheme

5.2.1 Overview of Profit Distribution of Asteroid Mining

In the future, it is highly possible that "poor" countries do not own the technology or fund for asteroid mining, while "rich" countries or companies dominate the industry. If the asteroid mining brings excess returns, it will inevitably makes rich countries richer and undermine the global equity. The solution to this is to let asteroid mining under strict supervision, and let the global mining board own the rights to distribute profits.

According to the spirit of the United Nations' Outer Space Treaty of 1967,[10] asteroid minerals do not belong to any country or person, and thus can be regarded as the common wealth of all mankind. Each sector should report their cost and output values, and the profits from asteroid mining. Every "citizen of the Earth" should be have a share.

The global mining board should own the rights to distribute the profit from asteroid mining. The reason we only consider the profit instead of total output value is to ensure that each sector conducting profitable asteroid mining would only make money from it. Except in the early stage of scientific research, economic profitability is a prerequisite for large-scale mining. If a type of asteroid mining loses money itself, it indicates that the mineral is not scarce or valuable enough, and thus the mining will not be worthwhile to be carried out. Thus we can assume that the total output value V_T surpasses the total cost C_T. And we can expect the total profit to P_T be positive:

$$P_T = V_T - C_T > 0 \tag{13}$$

We hope to divide the overall profits into roughly two parts. The first part is the Contribution Encouragement, which will take α of the overall profits. The second part will be used as Asteroid for Global Equity Fund (AGEF) to be managed by the United Nations to promote global equity. It will take β of the overall profits.

We can assume that the administrative and management expenses of the United Nation is relatively very small. It consumes only ε of the overall profit where $\varepsilon \ll \alpha, \beta$. Then we have:

$$\alpha\% + \beta\% \approx 1 \tag{14}$$

5.2.2 Profit for Contribution Encouragement

Those involved in asteroid mining can be divided into two categories—state-affiliated institutions and private corporations. We call them asteroid mining sectors in this paper. Currently most sectors involved in outer space activities are state-affiliated institutions, such as the National Aeronautics and Space Administration (NASA) from the U.S., Russian Federal Space Agency (RKA), and China National Space Administration (CNSA). From observations of the current mining industry, we can expect private corporations also involve in asteroid mining in the future.

The proportion α of the overall profit will be used for Contribution Encouragement. It includes direct compensation, which they can keep for their own and indirect compensation, which will be distributed by authoritative

The asteroid mining itself is the source of our profits. We hope that sectors conducting asteroid mining would keep proportion λ $(\lambda < \alpha)$ of all their profits for their own. It is a direct encouragement for them to enhance production enthusiasm and make more profits.

We will also distribute proportion $\mu = \alpha - \lambda$ of the overall profit according to different sector's contribution to the shared part of asteroid mining. Since asteroid mining is a huge and challenging task, it will require the collaboration across countries and companies. In this way can we reward the sectors that actively share technologies and platforms.

We evaluate the "contribution to the shared part" in the four categories: technology contribution, space station contribution, public transportation contribution, mining help contribution. The UN experts will evaluate each sector's contribution in each category. For example, asteroid mining may be dangerous and have high casualty rate. If a corporation sends accompanying doctors and offers medical help to all injured or sick workers, it would likely to receive a high score in "mining help contribution".

Then use Weight Entropy Model (EWM)[11] to determining the weight of each contribution category. It is objective

In each category, for the i^{th} sector and j^{th} index, the weight of it, f_{ij}, is calculated as follows:

$$f_{ij} = \frac{r_{ij}}{\Sigma_{i=1}^{m} r_{ij}} \tag{15}$$

where m is the total number of asteroid mining sectors.

And the function of information entropy, e_j, is calculated as follows:

$$e_j = -ln(\frac{1}{n})\Sigma_{i=1}^{m} ln(f_{ij}) \tag{16}$$

Finally, we attain the weight of the j^{th} index W_{Ej} in each category, calculated as follows:

$$W_{Ej} = \frac{1 - e_j}{m - \Sigma_{j=1} n e_j} \tag{17}$$

Finally, we can compute the contribution score c for each sector with the contribution in each category c_j and the weights obtained.

$$c = \Sigma_{j=1}^{4} W_{Ej} \cdot c_j \tag{18}$$

5.2.3 Profit for Global Equity Fund

This part of the overall profit will be used for Global Equity Fund (GEF) to be managed by the United Nations or global mining board to promote global equity in ways including but not limited to research and development, spaceport building, and subsidize enterprises. It will take proportion β of the overall profits.

We obtain the Fulfillment Score F for all the countries in section 2.1. They are in the range $[0,1]$. The higher a country's F is, the more fulfilled people in that country may feel. According to the principle of Asteroid Mining for Global Equity Fund, the fund should be used to promote global equity. People living in poverty, hunger or those whose basic needs are not met have the right to claim a larger part.

We will assign a general weight for each person w_p to get the fund according to the country's Fulfillment score. We hope to convert the Fulfillment Score F into exponential, which represents the significant differences in people's needs. After careful consideration, we choose e as the base. And we minus one from them to convert the lowest weight from 1 to 0. The formula is as follows:

$$w_p = e^{(1-F)} - 1 \tag{19}$$

Notice that the original Fulfillment Score F is in the range $[0,1]$. After our transformation, the weights are in the range $[0, e-1]$, with the smallest 0 converted to $e-1$ and the largest 1 converted to 0. The distribution is shown as follows.

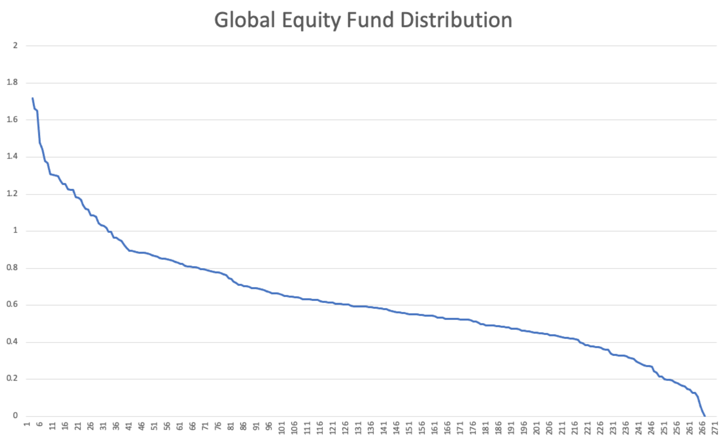

Figure 8: Global Equity Fund Distribution

The formula for the total fund distributed to a country is as follows:

$$w_c = (e^{(1-F)} - 1)P \tag{20}$$

where P represents the population size of the country.

The fund will be distributed by country. In each country, the fund should be used to help the people to fulfill life needs under the supervision of United Nations Special Observers and committees.

5.2.4 Balancing the Profit Distribution for Contribution Encouragement and Global Equity Fund

We divide the overall profits into two parts—proportion α of the overall profits as Contribution Encouragement and proportion β for Global Equity Fund. In this part, we will discuss how to balance the two parts.

If the proportion of profits used for Global Equity Fund β is too small, most of the profits will go into the pockets of large countries and companies with asteroid mining capabilities. It may have the risk of exacerbating global inequality. If the proportion of profits used for Contribution Encouragement α is too small, people's enthusiasm for asteroid mining will decrease. They will have no incentive to expand mining scales, or develop innovative technologies for continuous improvement. As a result, the overall profit will dramatically decrease, and the amount used for Global Equity Fund may decreases.

Let's say we hope that the amount of profit P_β used for Global Equity Fund will be maximum. It follows that

$$P_\beta = P_T\beta = P_T(1-\alpha) \rightarrow maximum \tag{21}$$

We assume that the marginal ratio of total profits and proportion of contribution encouragement is r. That is

$$\frac{\partial P_T}{\partial \alpha} = r \tag{22}$$

To get the maximum P_β with respect to α, we set

$$\frac{\partial P_\beta}{\partial \alpha} = 0 \tag{23}$$

Thus

$$\begin{aligned}\frac{\partial P_\beta}{\partial \alpha} &= \frac{P_T(1-\alpha)}{\partial \alpha} \\ &= \frac{\partial P_T}{\partial \alpha}\cdot(1-\alpha) + \frac{\partial(1-\alpha)}{\partial \alpha}\cdot P_T \\ &= r\cdot(1-\alpha)+(-1)\cdot P_T = 0\end{aligned} \tag{24}$$

We do not know the exact relationship between P_T and α. For simplicity, assume there exists a linear relationship that

$$P_T = r\alpha + P_0 \tag{25}$$

When $\alpha = 0$, the total profit P_T cannot be negative. We can assume that $P_0 = 0$ accordingly since people's asteroid mining activities will not get compensated directly. But in reality, there are still many outer space activities or explorations even without direct compensations. Moreover, people can still get indirect compensations from the Global Equity Fund. Therefore, we can assume that $P_0 > 0$.

Thus

$$\frac{\partial P_\beta}{\partial \alpha} = r\cdot(1-\alpha)+(-1)\cdot(r\alpha+P_0) = 0 \tag{26}$$

We solve

$$\alpha = \frac{r + P_0}{2r} = \frac{1}{2} + \frac{P_0}{2r} \tag{27}$$

Since r is a constant, the optimum value of α is only dependent on P_0. And we get that α should always be larger than $\frac{1}{2}$.

5.3 International Research Collaboration Program

Research and planning is an essential step for the long-term mission of exploring and taking advantage of the resources in outer space. The United Nations may initiate an International Research Collaboration Program (IRCP), which consists of experts all over the world to research the possibility of asteroid mining: target asteroids, equipment design, travel planning, cost management, and so on. Although each country may research on their own, the world would be able to share technologies via the program and advance together at a steady pace, bringing up countries that potentially fall behind in the asteroid mining journey. The United Nations may provide or raise funds for the research team. Therefore, countries would all increase their research and development component, and thus the GEI may become smaller.

5.4 Asteroid Mining Strategic Partnership

Countries may sign a specific treaty and form a strategic partnership with one or more other countries. Although each country has its free will to form partnerships, the UN could guide the formation of partnerships to ensure countries with high and low Fulfillment Scores and well-mixed. In the partnership, countries need to strategically advance the asteroid mining industry together,[12] including but not limited to providing a friendly environment to initiating joint venture in asteroid mining, exchanging mineral resources in a mutually beneficial way, providing technological help or resources to conduct asteroid mining activities. In such a way, the natural resource depletion, net national income, and research and development variables in the GEI model will drive GEI down, meaning a more equitable world. Furthermore, the world would advance in a more efficient way, since countries with less ability to develop the industry would quickly benefit from directly learning technologies from partners that have already developed.

5.5 Anti-Monopoly and Anti-Oligopoly

As illustrated in the previous section, monopoly and oligopoly market would cause a higher GEI, meaning that countries that first enter the market may have abusing power to decide the price. Therefore, countries need to agree to not monopolize in the market. By preventing monopoly and oligopoly market, the society would avoid the situation that countries have larger difference in variables like net national income, natural resources depletion, and employment in the GEI model, which would result in a high GEI, meaning a less fair world.

6 Strengths and Weaknesses

6.1 Strengths

Firstly, our calculation of Fulfillment Scores takes 10 variables from different perspectives and all five levels of Maslow's Hierarchy of Needs into consideration. We use the Analytic

Hierarchy Process (AHC) to give them reasonable weights. Therefore, our measure of equity is multi-dimensional, taking into account the all-round development and happiness of human beings.

Secondly, we divide the profits from asteroid mining into two parts—one for Contribution Encouragement and the other used for a Global Equity Fund (GEF). This decision considers both the interests of asteroid mining sectors and ordinary people. We also discuss how to balance the two parts, which is a trade-off between efficiency-fairness. We share some ideas about the dilemma, and apply an Optimization Model to gain insights.

6.2 Weaknesses

One weakness of our models is that we do not have the actual data in asteroid mining. It will also be too hard to simulate the data. The lack of data inhibits our ability to adjust or validate our models. We are looking forward to the day that large-scale asteroid mining actually happen and we have the available data to build better models.

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