Impacts of Asteroid Mining on Global Equity

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Abstract. With rapid development in technology, asteroid mining may become a reality in the near future. This paper focuses on the possible impacts of asteroid mining on global equity. In order to evaluate the global equity situation, we developed a global equity assessment model with 5 superior indicators and 18 inferior indicators, in which analytic hierarchy process (AHP) and entropy weight method (EWM) are used to obtain the combined weight, and TOPSIS was used to calculate the National Strength Index (NSI). Then Global Equity Index (GEI) is obtained by measuring the dispersion degree of NSI. Hierarchical grouping. Finally, hierarchical cluster analysis is used to determine which countries are capable of asteroids mining, and the changes of NSI and then GEI are obtained through the mutual iteration of the value obtained from minerals and NSI. Our analysis of data from 30 European countries from 1995 to 2020 shows that unregulated asteroid mining increases global inequity, depending on factors such as the total value of minerals and the difficulty of mining. Our study provides theoretical support and policy recommendations for reducing potential inequities caused by asteroid mining.

Keywords: Global Equity; Asteroid Mining; AHP; EWM; TOPSIS; Hierarchical Clustering.

1. Introduction

With the rapid development of space technology and a better understanding of the composition of celestial bodies, the use of space resources has become an increasingly important topic. In recent years, the utilization of space resources has been at the top of the agenda of many space agencies [1].

The prospect of space mining, a major source modality for outer space resources, has long been part of the scientific, legal, and cultural landscape. The general accessibility of asteroids and comets has been demonstrated by the orbital flights of ESA's Rosetta mission, JAXA's Hayabusa, JAXA's Ryugu of Hayabusa and Bennu of OSIRIS-REx [2].

The use of natural resources in outer space has the potential to greatly enhance our ability to explore and utilize outer space. Given that current space law does not directly specify how benefits are to be shared, determining how these resources are to be shared requires clear international oversight. Significant differences remain between countries at different levels of economic and scientific development.

Specifically, spacefaring nations are reluctant to sacrifice those who cannot afford to invest or obtain "hard-won" benefits on their own, while developing countries are eager to have an equitable distribution of benefits from jointly owned sources [3]. At the same time, because of the economic and scientific superiority of powerful nations in the race for these assets, competition with each other actually increases not only their wealth but also the stakes for land and related property or assets [4]. This can lead to making the stronger countries stronger and the weaker countries weaker, thus making global inequity worse. Therefore, in order for all countries to reap these benefits and avoid the tragedy of the anti-commons, a fair and reasonable benefit-sharing system is essential.

Our goal is to find a reasonable way to assess global equity and to characterize changes in global equity. On this basis, we would explore the impact of asteroid mining without strong supervision by international organizations on global equity.

2. An Assessment of Global Equity

In this section, we put forward a methodology to quantify the equity in a zone and a historical period. Firstly, we select superior indicators and inferior indicators related to the comprehensive developing state of countries, and every inferior indicator belongs to a certain superior one. AHP (Analytic Hierarchy Process) and EWM (Entropy Weight Method) are implemented upon the superior and inferior indicators respectively to calculate their weights of them. According to both weights, redistribution of inferior weights is done so that we can get the combination weights. Using the combination weights, TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is implemented to calculate the comprehensive strength of countries as NSI (National Strength Index). Finally, we analyze the dispersion degree of NSI to determine the GEI (Global Strength Index).

2.1 Superior and Inferior Indicators

The measurement of global equity is to be related to the current combined strength of each country. The combined strength of a country is measured by numerous dimensions. Therefore, we believe that a reasonable global equity measurement system needs to include five aspects simultaneously: demographic, economic, social, scientific and technological, and military. To measure the global equity of a country, we give five superior indicators, $\{P, E, S, T, M\}$, denoting Population, Economics, Society, Technology, Military respectively.

There are many inferior indicators under each superior indicator. 18 inferior indicators and 5 superior indicators are considered as shown in Figure 1.

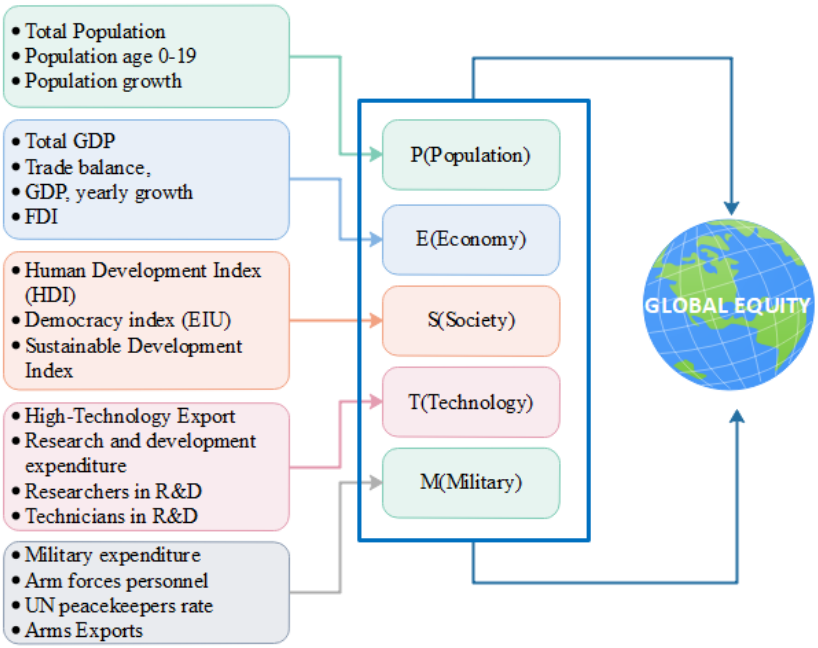


Figure 1. Superior and inferior indicators

2.1.1 Population Index (PI)

Population is a very important factor. The size of a country's population means the amount of resources that country needs. We can only call it global equity if the interests of the majority are maintained. Therefore, we choose the indicators: Total Population for each country, the percentage of the population aged 0-19 years in the total population and the population growth rate.

2.1.2 Economics Index (EI)

The economic status of a country is an important indicator of its overall national power. Countries with more developed economies have more funds available to invest in asteroid mining. Therefore, we choose the indicators: Total GDP, Trade balance as a percentage of GDP, annual growth rate of GDP, foreign direct investment.

2.1.3 Society Index (SI)

A country's social situation is important for measuring global equity. Social factors influence the stability of a country now and its sustainable development in the future. Thus we choose the indicators: Human Development Index (HDI), Democracy index (EIU), Sustainable Development Index.

2.1.4 Technology Index (TI)

Technology is the first productive force. The higher technology level of a country means more advanced technology to asteroid mining. Therefore, we choose the indicators: High-Technology Export (billion $), Research and development expenditure (billion $), Researchers in R&D (per million people), Researchers in R&D (per million people), Technicians in R&D (per million people).

2.1.5 Military Index (MI)

Military power plays an important role in international status. The higher MI means greater voice in the international arena. Thus we choose indicators: Military expenditure (million $), Arm forces personnel, total (k), UN peacekeepers rate (per 100 000 people), Arms Exports (million $).

2.2 The Weights of Indicators

The determination of the weights. In order to calculate the weights of 18 inferior indicators and 5 superior indicators we choose and finally get more objective results, we chose the Analytic Hierarchy Process (AHP) for the subjective weighting analysis and the Entropy Weight Method (EWM) for the objective weighting analysis among many methods. This combination of subjective and objective weighting methods can better work and the essence is that the rich experience of the expert (decision maker) acts on the data which have the high sensitivity, ultimately reducing the error of the data and improving the accuracy.

2.2.1 Determining the Weights of Superior Indicators by AHP

AHP is a combination of qualitative and quantitative, systematic and hierarchical analysis method. The principle is that a problem is decomposed into different components according to the nature of the problem and the goal to be achieved. Factors are aggregated and combined at different levels so that the problem can be ultimately reduced to the determination of the relative importance of the lowest level relative to the highest level or the relative order of relative importance [5].

We divide the whole procedure into 3 steps:

Establish hierarchy structure model, as shown in Figure 2.

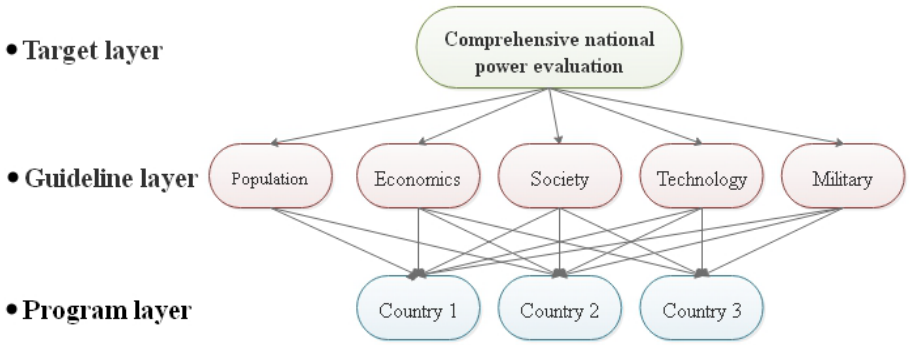


Figure 2. Hierarchy Structure

Construct judgement matrix of superior indicators:

$$A = (a_{ij})_{n\times n} \quad (1)$$

where A is the judgement matrix; a_{ij} is the importance of indicator x_i towards indicator x_j; n is the quantity of superior indicators. The numbers from 1 to 9 are chosen to assess the preference and vitality of the ith indicator towards jth indicator. Larger numbers indicate greater importance. The judgement matrix is shown below reasonably.

$$A = \begin{bmatrix} 1 & 1/3 & 2 & 1 & 3 \\ 3 & 1 & 5 & 2 & 6 \\ 1/2 & 1/5 & 1 & 1/4 & 1/2 \\ 1 & 1/2 & 4 & 1 & 3 \\ 1/3 & 1/6 & 2 & 1/3 & 1 \end{bmatrix} \quad (2)$$

The order of elements in matrix is Population, Economy, Society, Technology and Military.

Perform a consistent check and calculate the weights of each superior indicators on Matlab.

The judgement matrix must pass the consistent check to avoid the paradox, which the Concordance ratio CR must less than 0.1.

$$CR = \frac{CI}{1.12} \quad (3)$$

where $CI = \frac{\lambda_{max}-5}{4}$, and λ_{max} is the largest eigenvalue of marix A.

Then we use the arithmetic mean to get weights ω .

$$\omega_{1i} = \frac{1}{5}\sum_{j=1}^{5} \frac{a_{ij}}{\sum_{k=1}^{5} a_{kj}} \quad (4)$$

Above this, weights of Population, Economy, Society, Technology and Military are obtained.

2.2.2 Determining the Weights of Inferior Indicators by EWM

The basic idea of the is to determine the objective weight according to the variability of the index. If the information entropy of an index is smaller, it indicates that the index value has a greater degree of variation. The more information it provides, the greater the role it can play in the comprehensive evaluation, and the greater its weight, and vice versa [6].

We will use EWM to process X matrix after the standardization to calculate the weights of inferior indicators.

We divide the whole procedure into 3 steps:

Calculate the probability matrix P.

A specific dataset is needed to calculate the matrix P. Then we acquire numbers about 18 aspects from the dataset. P is set to describe the feature proportion of every indicator in a country.

$$p_{ij} = \frac{b_{ij}}{\sum_{i=1}^{n} b_{ij}} \quad (5)$$

Where p_{ij} is the feature proportion of the country i in indicator j, b_{ij} is the value of indicator j of country i.

According to the information theory and concept of information entropy, we can calculate the information entropy E_i for each inferior indicator:

$$E_i = -ln(n)^{-1} \sum_{j=1}^{n} P_{ij} ln(P_{ij}) \quad (6)$$

After obtaining the information entropy, we apply normalization to the entropy to further get weights of inferior indicators.

$$w_{2i} = \frac{1 - E_i}{\sum_{i=1}^{n}(1 - E_i)} \quad (7)$$

2.2.3 Combination Weights

We normalize the weights w_{1i} calculated by Entropy Weight Method according to the superior indicators they belong to, and then multiply w_{1i} and w_{2i} which is calculated by the Analysis Hierarchy Process by the same class.

$$w_i = \frac{w_{1i} \times w_{2i}}{\sum_{i=m}^{n}(w_{1i})} \quad (8)$$

where w_{1i} is weights of inferior indicators calculated by EWM, w_{2i} is weights of superior indicators calculated by AHP, and inferior indicators whose weights are w_{1m} to w_{1n} are the subordinates to superior weight with the weight w_{2i}.

2.3 National Strength Index

After determining the combination weights through the above methods, we decided to use the weighted TOPSIS method to calculate the NSI of each country [7], which measures the country's aggregate power. The higher the NSI, the stronger the comprehensive national strength of the country.

We will preprocess the dataset through the normalization and positivization. The former is based on $X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}}$, where X_{max} and X_{min} are the maximum and minimum of the indicator, and the latter is based on $X_{posi} = X_{max} - X$, where X_{max} is the maximum of the indicator, when the inferior indicator plays a negative role in the global equity.

After using the above normalization and positivization process we will get the normalization matrix X, now we will calculate the optimal distance and the worst distance:

$$\begin{aligned} X^+ &= (max\{x_{11}, x_{11}, \cdots, x_{n1}\}, max\{x_{12}, x_{12}, \cdots, x_{n2}\}, \cdots, max\{x_{1m}, x_{1m}, \cdots, x_{nm}\},) \\ &= (X_1^+, X_2^+, \cdots X_m^+) \\ X^- &= (min\{x_{11}, x_{11}, \cdots, x_{n1}\}, min\{x_{12}, x_{12}, \cdots, x_{n2}\}, \cdots, min\{x_{1m}, x_{1m}, \cdots, x_{nm}\},) \\ &= (X_1^-, X_2^-, \cdots X_m^-) \end{aligned} \tag{9}$$

where X^+ represents the optimal distance and X^- represents the worst distance.

Calculate the proximity of each indicator to the optimal distance and the worst distance :

$$NSI = \frac{D_i^-}{D_i^+ + D_i^-} \tag{10}$$

where $D_i^+ = \sqrt{\sum_{j=1}^{18} w_i (X_i^+ - x_{ij})^2}$, $D_i^- = \sqrt{\sum_{j=1}^{18} w_i (X_i^- - x_{ij})^2}$.

The comprehensive strength of a country is positively correlated with the NSI. The more powerful the nation is, the bigger its NSI is.

2.4 Global Equity Index

As is mentioned above, the calculattion of NSI for different countries is completed. Finally, the equity situation in this area is evaluated by calculating the degree of disparity of NSI. We will use the standard deviation to quantify this concept.

After normalizing the NSI for m countries in a region, we calculate the standard deviation, denoted as SD that can be obtained as:

$$SD = \sigma\left(\frac{[NSI_1, NSI_2, \ldots, NSI_m]}{\sum_{i=1}^{m} NSI_i}\right) \tag{11}$$

where NSI_i is NSI of ith country and $\sigma(\{a_i\})$ denotes the standard deviation of array $\{a_i\}$.

It follows from mathematical principles that SD is taken to the maximum value when taking the sequence as $[\frac{\sum_{i=1}^{m} nsi_i}{\sum_{i=1}^{m} nsi_i}, 0, \cdots, 0]$ whose sum of a sequence is constant. Therefore, $SD_{max} = \sqrt{\frac{m-1}{m^2}}$.

Now we introduce the Global Equity Index (GEI). The final GEI of the region can be obtained:

$$GEI = 1 - \frac{SD}{SD_{max}} \tag{12}$$

The higher GEI represents higher degree of the equity. The value range of the GEI is [0,1].

3. Impacts of Asteroid Mining

3.1 Countries are Capable of Asteroid Mining

First, we need to measure a country's asteroid-mining capacity. It is reasonable that economics and technology are the main factors affecting a country's asteroid mining capability, which is consistent with popular perception. Thus, through multiplying the 8 inferior indicators belonging to Economics Index and Technology Index by their corresponding weights and standardizing them in the same way as calculating NSI, the values of EI and TI can be obtained, which can be used to measure the economic and technological level of a country.

Then these countries should be categorized. We carry out Hierarchical Clustering analysis by the Method of Sum of Squares of Deviations (Ward's minimum variance algorithms) using EI and TI as variables [8]. By Ward's Method, the sum of squares of deviations between samples within the same class should be small, while ones between classes should be large, making it hard to merge two large classes, which in line with our practical requirements.

Let class G_K and class G_L be merged into the new class G_M, then the sums of the squares of the deviations of G_K, G_L and G_M are as follows.

$$\begin{cases} W_K = \sum_{i \in G_K} \left(x_{(i)} - \bar{x}_K\right)^T \left(x_{(i)} - \bar{x}_K\right) \\ W_L = \sum_{i \in G_L} \left(x_{(i)} - \bar{x}_L\right)^T \left(x_{(i)} - \bar{x}_L\right) \\ W_M = \sum_{i \in G_M} \left(x_{(i)} - \bar{x}_M\right)^T \left(x_{(i)} - \bar{x}_M\right) \end{cases} \tag{13}$$

where $\bar{x}_K$, $\bar{x}_L$ and $\bar{x}_M$ represent the center of gravity of G_K, G_L and G_M respectively. Thus W_K, W_L and W_M reflect the degree of dispersion of samples within each class. If G_K and G_L are close to each other, the sum of the squares of deviations increased by the combination of them should be smaller, and vice versa. So we define the squared distance between G_K and G_L as

$$D_{KL}^2 = W_M - (W_K + W_L) \tag{14}$$

At this point, we can perform hierarchical clustering according to the defined distances between classes. Then, we divide all the countries according to the actual clustering results, and delimit who can mine asteroids.

3.2 The Changes Asteroid Mining Brings to GEI

In order to investigate the impact of asteroid mining on GEI, we first need to know the NSI changes caused by it in various countries. Now we assume that the average annual total actual value of asteroid mineral resources proved and able to be exploited in the future plan is V_{At}, which takes into account changes in the value of mineral resources as they increase and strips out the cost of asteroid mining. We assume that the value thus obtained has a one-year delay.

Next, we calculate the value of the asteroid minerals a country can mine. As mentioned earlier, a country's asteroid mining capacity is mainly measured by economic and technological levels. The sum of economic and technological weights calculated by AHP is more than two thirds of the total according to Formula (2). Therefore, we can reasonably use NSI to characterize a country's asteroid mining capacity. In the absence of effective management by international organizations, countries will acquire as many resources as possible in order to maximize their own interests. Thus the actual value of asteroid minerals the ith country can exploit in jth year is

$$V_{aij} = V_{At}(10NSI_{ij}) \frac{NSI_{ij}}{\sum_{i=1}^{n} NSI_{ij}} \quad (i = 1,2,\dots,n) \tag{15}$$

where n represents the number of such countries capable of asteroid mining and NSI_{ij} denotes the NSI of ith country in jth year. $10NSI_{ij}$, as a coefficient, represents the profit conversion rate.

Then, we can obtain $NSI_{i(j+1)}$ by adding V_{aij} to the country's GDP $(j+1)$th year, which can be used tu calculate $V_{ai(j+1)}$. By doing this over and over again, we can get the NSI's change of a country year by year.

Finally, we calculate GEI for each year based on the NSI obtained by iteration in order to find how asteroid mining affects global equity.

4. Case Study: Europe

In order to validate our equity evaluation model and explore the impacts of asteroid mining, we choose 30 countries in a typical region: Europe. Why we choose Europe is that the data of countries in Europe are relatively complete so we can observe the changes of GEI over a long period, and there are different categories of countries, which is representative for global situation.

Before we start applying our model, we define this European region. The 30 countries in the European region applied to the model are completely independent of the rest of the world. At the same time the region consists of only these 30 countries, otherwise the model would have a large error. That is, the region consisting of the selected countries is considered as an overhead world.

First, we choose the data of 2014 to calculate NSI, judging its validity based on public perception. Then we take data from 1995 to 2020 and analyse the change in equity over 35 years. Finally, we assume different mineral values and mining difficulties to explore the changes in GEI caused by them.

4.1 Equity Situation in Europe

Before all else, AHP and EWM are comprehensively used to obtain the weight of 5 superior indicators and 18 inferior indicators, and the results are shown in Figure 3.

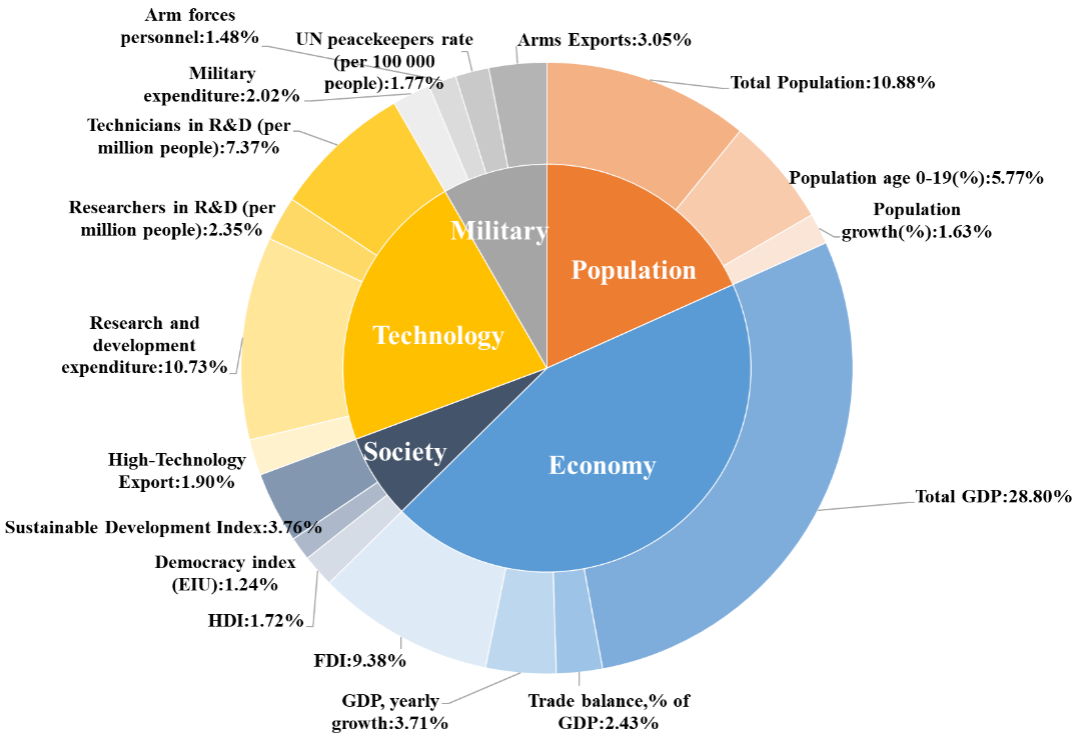


Figure 3. Weight of each indicator

Next, we use weighted TOPSIS method to calculate NSI of each country and rank them. The results are shown in Table 1.

Table 1. NSI ranking in 2014

Ranking	Country	NSI/%	Ranking	Country	NSI/%
1	Germany	10.78	16	Austria	2.81
2	France	8.51	17	Finland	2.78
3	Italy	5.55	18	Iceland	2.71
4	Spain	4.68	19	Hungary	2.67
5	Norway	3.62	20	Lithuania	2.52
6	Netherlands	3.57	21	Romania	2.51
7	Ireland	3.40	22	Latvia	2.45
8	Sweden	3.31	23	Estonia	2.32
9	Switzerland	3.18	24	Bulgaria	2.25
10	Slovenia	3.15	25	Portugal	2.23
11	Malta	3.13	26	Greece	2.14
12	Poland	3.08	27	Croatia	2.08
13	Czech Republic	3.07	28	Albania	1.97
14	Belgium	3.05	29	Serbia	1.90
15	Denmark	2.91	30	Bosnia and Herzegovina	1.68

To visualize the results of NSI, we created the heat map shown in Figure 4.

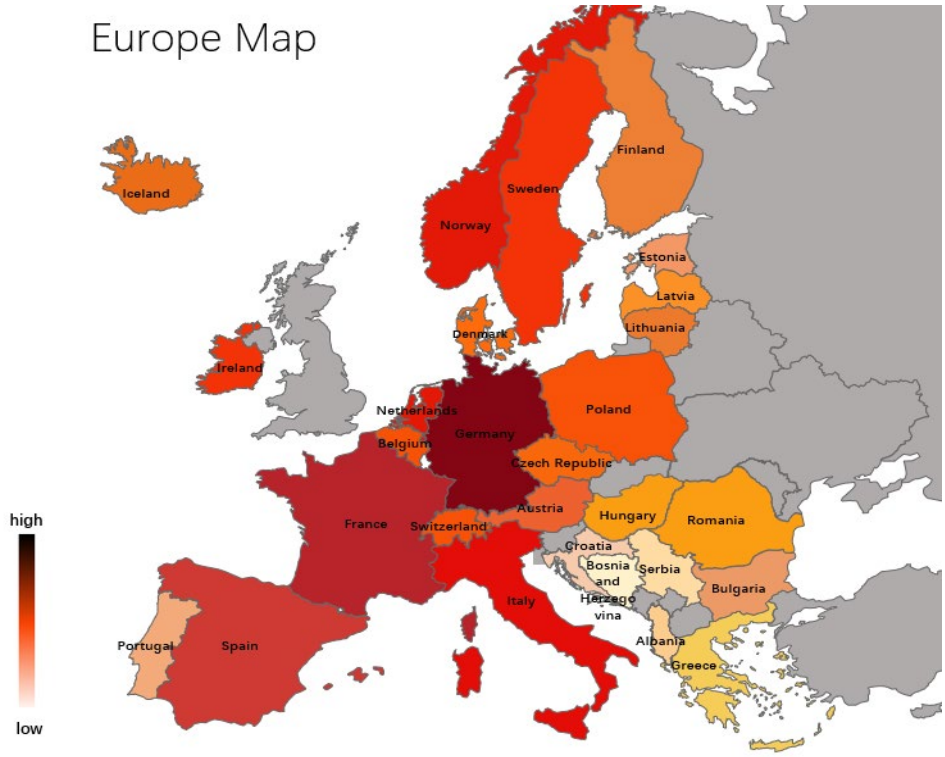


Figure 4. Heat Map of NSI in Europe

From the figure, we can conclude that Germany, France, Italy and Spain occupy the top positions with an absolute advantage, while Serbia, Bosnia and Herzegovina are at the bottom, which is in line with the general recognition of the international community today.

After verifying the validity of NSI, we can calculate GEI in 2014. It's obvious that $SD_{max} = 0.1795055$ when $n = 30$ and $SD = 0.0188173$ in 2014 according to Table 1. Therefore, $GEI = 0.89517$ from Formula (12). Thus, we can use the same method to obtain GEI from 1995 to 2020 and draw the result into a broken line graph, as shown in Figure 5.

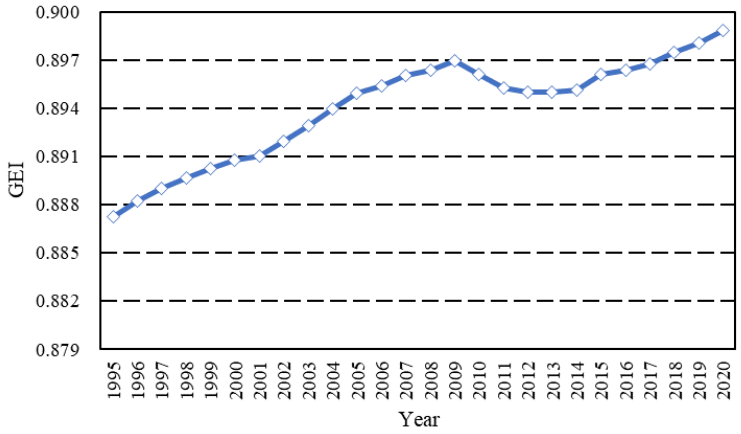


Figure 5. The change of GEI in Europe form 1995 to 2020

From the graph, although there may have been a brief dip in the years after 2008 due to the subprime crisis, the GEI among the 30 European countries is increasing overall as time goes by, which means regional inequity also gradually decreases. This is a logical tendency so the validity of the model has been verified.

4.2 Impacts of Asteroid Mining on Equity in Europe

We select the data in 2014 as representative values of asteroid mining capacity of countries from 1995 to 2020 and conduct clustering analysis by Ward's Method. The result are shown in Figure 6.

From the figure, we consider two cases based on how difficult it is to mine asteroids:

Case1: Mining is relatively difficult, all the countries are divided into two groups, and only two countries in the first group had the capacity of asteroids mining.

Case 2: Mining is relatively easy, all the countries are divided into four groups, and eight countries of the first three groups have capacity while the last group do not.

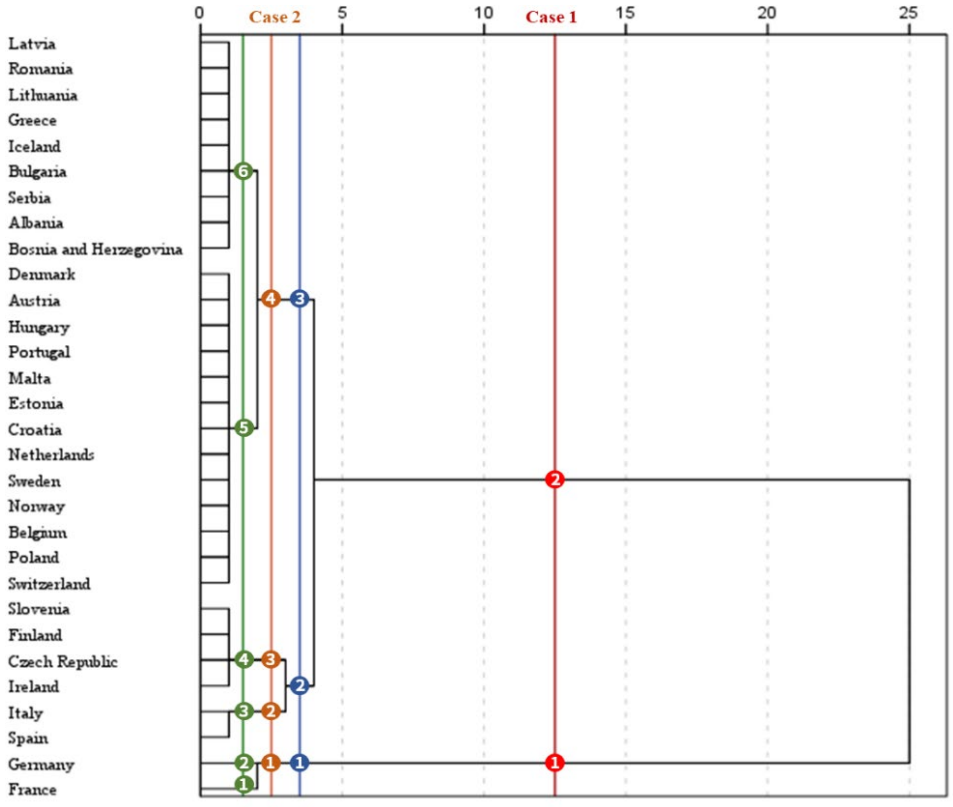


Figure 6. Hierarchical clustering analysis with Ward's Method

Then we assume that asteroid mining has been possible since 1995 and set two differenttotal actual value V_{At}s, \$80 billion/year and \$1600 billion/year, for each case. Then we calculate V_{aij} according to Formula (15), using 1995 as the starting year for our calculations. NSIs for each country between 1995 and 2020 are obtained after 25 iterations. Finally, we can calculate the GEI for the 25 years according to the previous method, and the result is shown in Figure 7.

From the picture we can draw the following three conclusions.

Comparing Curve 0 and other curves, in the absence of effective international oversight, asteroid mining would exacerbate inequality.

Comparing Curve 0, 1 and 2, the higher value of asteroid minerals would lead to greater inequality. We can come to the same conclusion by comparing Curve 0, 3 and 4.

Comparing Curve 0, 1 and 3, within limits, the more difficult it is to mine asteroids, the fewer countries that can exploit them, and the fewer can benefit, making it less fair. We can come to the same conclusion by comparing Curve 0, 2 and 4.

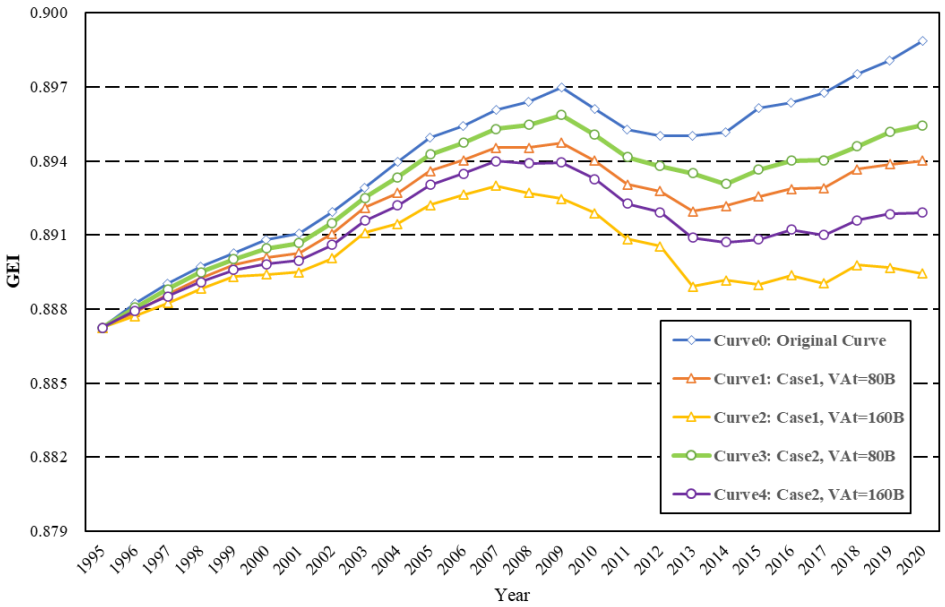


Figure 7. The change of the GEI under the influence of asteroid mining

5. Conclusion

This paper develops a Global Equity Index (GEI) based approach for assessing global equity and a model of the impact of asteroid mining on GEI. Thirty European countries are selected to study the changes in regional equity over the 25-year period from 1995 to 2020 under the assumption that asteroid mining has been available since 1995.

This is a powerful study on one of a series of problems that may be brought about by asteroid mining in the future, which makes up for the deficiency of existing research to some extent, and also provides a theoretical basis and enlightening thought for solving the same type of benefit distribution problem (such as public marine oil field exploitation problem), which has a certain reference significance.

The results reveal two main things. First, the inequality of the European region, represented by these 30 European countries, has been decreasing on the whole from 1995 to 2020, and the region has become more equal. Secondly, without the effective supervision of international organizations, asteroid mining will increase inequality, which will be aggravated by the increase in the total value of asteroid minerals and the increase in the difficulty of mining within a certain range.

This phenomenon calls for effective regulation of asteroid mining when it becomes a reality. First, the total value of the asteroid minerals mined needs to be rationally and systematically arranged and

distributed, rather than just gobbled up by powerful nations alone. Second, a stronger country would need to provide economic and technological support to its peers who are weaker to make it easier for them to mine asteroids, or the stronger one would be punished accordingly.

Compared to other studies of this type, our model fully considers the impact of various factors in reality on the model. The parameters are closely related to the actual data, and can be adjusted appropriately, which fully reflects the adaptability of the model. In terms of algorithms, we utilize combination weights and clustering analysis which improve the reference for practical policies. In future resource allocation problems, it can be a good measurement tool to promote equity issues.

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