Problem Chosen	2022 MCM/ICM Summary Sheet	Team Control Number
F		2218390

Asteroid Mining's Impact on Global Equity

What is global equity, and how will asteroid mining impact it? This was the guiding question we sought to answer in our paper. We define **global equity** as impartiality, fairness, and integrity regarding social and economic policy. It considers systematic inequalities to ensure a standardized level of access to opportunity. Equity realizes differing circumstances require differing allocation of resources to reach equal outcomes. It is an egalitarian social structure built on nondiscriminatory economic policy that allows all people, regardless of current financial status, to gain the opportunity to thrive.

We created a **TOPSIS model** to evaluate each region based on disparate criteria from the United Nations Human Development report to quantify global equity. We chose these criteria based on our definition of global equity and what we consider an equitable society. We foresee an equitable society as one where everyone has equal opportunity and are unconstrained by social factors such as discriminatory practices. To this end, our parameters were **Human Development Index (HDI), Gross National Income per capita (GNI), the Education Index (EI), and the Unemployment percentage.** We stratified these variables by region to find a baseline equity score per in order tocompare it to equity scores after asteroid mining to determine how it would impact global equity.

We believe that the best metric for evaluating how asteroid mining will impact global equity will be similar to the effect of previous booms in mining towns and commodity price depressions in the past. When examining previous mining booms, we found that exploration and mining activities can generate wealth and socio-economic growth, primarily through **Community Development Agreements (CDA)**. With community development agreements, underdeveloped nations can increase employment with business and develop economic activity through spin-off opportunities. Mining can generate benefits that outlive the mine itself and create long-lasting economic opportunities.

To capitalize on the immense profitability of these mines, we recommend amending the Outer Space Treaty to tariff the profits and disburse them to emerging economies to improve national investment in these countries and boost economic development. Mineral deposits should also be equitably dispersed to enhance industrial development, in a sense creating a **Community Development Agreement** with corporations and the United Nations. Since asteroid mining will drive the value of precious metals to near zero, we encourage countries worldwide to strengthen their fiscal and monetary policy by encouraging diversification of exports from precious metals and investing to diversify their physical and human capital, thereby improving global equity.

Problem F: All for One and One (Space) for All!

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1 Introduction

1.1 Overview of the problem

What is global equity, and how will asteroid mining impact it?

This was the guiding question we sought to answer in our paper. We define **global equity** as impartiality, fairness, and integrity regarding social and economic policy. To quantify this, we chose four metrics that reflected our definition of global equity: **Human Development Index (HDI), Gross National Income per capita (GNI), the Education Index (EI), and the Unemployment percentage.** We stratify these variable across 7 regions to generate a regional analysis of global equity.

Will the international promise of equity hold as humankind looks to harvesting space-based resources?

For our analysis, we assume that the primary method of space-based harvesting will be asteroid mining and that asteroid mining will be feasible both technically and economically at some point in the future. After researching asteroid mining and its progress for our model, we assume that it will become viable in 2050 [13]. Asteroid mining will allow humans to bring back valuable minerals to Earth with relative safety and responsible investment.

1.2 Parameter Definitions

Human Development Index (HDI): The Human Development Index is a statistic developed and compiled by the United Nations to measure various countries' social and economic development levels. It was established to emphasize individuals' opportunities to realize satisfying work and lives [10].

Gross National Income per capita (GNI): The Gross National Income is the total amount of money earned by a nation's people and business and is used to track and measure a nation's wealth over time. It includes the Gross Domestic Product, the final value of all goods and services produced in a country over time, plus the income received from foreign sources. We chose to include this in our definition of equity to see how equity varied from countries with differing levels of wealth [11].

Education Index (EI): The education index is measured by combining average adult years of schooling with expected years of education for students under 25. Education is a significant component of well-being and is regarded by economists as a critical measure of economic development and quality of life. We include this in our model to determine whether equity varies by education level and if economic activity generated by mining can improve educational well-being [12].

Unemployment %: We looked at the unemployment percentage by region to understand how global equity was affected by a lack of economic productivity. By including it in this model, we can discern if the economic impact of the mine will lower the unemployment percentage and thereby increase economic productivity.

1.3 Effect of Mining on Equity

The best metric to examine the global impact of asteroid mining is to look into the past and see how past commodity depressions impacted economic activity. Should it become feasible, asteroid mining would cause a massive depression in the price of precious metals. This will not lead to an economic collapse, contrary to the intuitive sense, because precious metals are no longer used as currency. Rock-bottom prices in precious metals can be repurposed for use in industrial aspects. For example, aluminum, the most abundant metal on the planet, was difficult to purify for most of human history and was more precious than gold; however, once the purification process became usable, it was employed in everything from airplanes to foil [19]. Flooding the economy with aluminum didn't cause an economic collapse and instead made society wealthier because refining improvements made everything else cheaper. A similar premise is likely to occur if asteroid mining becomes feasible. Gold and other precious metals will become abundant and free up resources to be used elsewhere and will create new industries that can thrive [18].

Historically, extractive industries have raised concerns regarding public policy, especially concerning how communities most directly affected by mining can share in its benefits. This question has traditionally been answered through initiatives from corporations; however, these initiatives are voluntary, which offers little certainty to communities and countries that the benefits of mining will be shared and its impacts managed. A second option is a regulation through policy; however, an ordinance is often inflexible and unresponsive, especially towards differing circumstances of individual communities affected by the mines. Therefore, we offer a third approach: negotiating contractual agreements between mining corporations and communities: **a community development agreement (CDA).** CDA's can ensure that affected communities can share in the economic benefits of mining and help minimize its adverse social effects [5]. For example, mining activities in Canada are used in partnerships with Aboriginal communities to create economic and social cohesion; the mine can generate benefits that boost the local economy and build community self-reliance [3].

Parameter Values Before Asteroid Mining

Data Gathered from UN Human Development Report [1]

Region	Education	GNI	Unemployment	HDI
Arab States	0.475433	1.299037	11.085714	0.638233
East Asia and the Pacific	0.530533	0.67925	3.842857	0.637967
Europe and Central Asia	0.6517	1.206170	9.114286	0.703733
Latin America and the Caribbean	0.598367	1.296277	7.257143	0.7035
South Asia	0.422267	0.38198	3.314286	0.542667
Sub-Saharan Africa	0.3825	0.301383	6.621429	0.464467
Small Island Developing States	0.5563	1.19905	6.371429	0.665667

TOPSIS Scores Before Asteroid Mining

Region	TOPSIS Score
Arab States	0.303935
East Asia and the Pacific	0.538878
Europe and Central Asia	0.647391
Latin America and the Caribbean	0.587438
South Asia	0.371940
Sub-Saharan Africa	0.350228
Small Island Developing States	0.537154

2 Modeling Methodology

2.1 Model Design

To quantify global equity, we used a TOPSIS model. When determining weights of indexes, subjective fixed weight methods such as the Delphi method, expert survey method, and AHP are often used. However, we disregarded these methods as they could lead to deviations in the indexes' weights due to subjective factors. [2]

We instead use the TOPIS Method(Technique for Order Preference by Similarity to Ideal Solution). A numerical method for multi-criteria decision-making. It is a broadly applicable and useful for evaluating disparate criteria. TOPSIS aggregates a set of alternatives by identifying weights for each criterion, normalizing scores, and determining the geometric distance between each ideal alternative. The main benefit of using the TOPSIS model is that it normalizes incongruous data such as our parameters and the compensatory methods behind the model, such as the normalization, allow for trade-offs between criteria which provides a more realistic model than non-compensatory methods [8].

The TOPSIS Model was computed as follows:

Decision Matrix

1. We constructed an empty evaluation matrix consisting of m alternatives (regions) and n criteria (parameters), the **j**th index's value in the ith parameter is (x_{ij}) , the decision matrix is then:

$$(x_{ij})_{m\times n}$$

2. For each parameter, we averaged the values over the 28 year span given by the data to get reasonable values for the evaluation matrix.

$$A = \frac{1}{28}\sum_{i=1}^{28} a_i$$

Determination of the weighted decision matrix

3. Different factors have different influences on higher education so in order to weigh the parameters reasonably we use Principal Component Analysis (PCA) and adopt the eigenvalue method [7]:

$$AW = \lambda_{max} W$$

Where λ_{max} is the largest eigenvalue of the evaluation matrix A and W is the eigenvector containing the weights for each parameter.

The weights were given as:

Education	GNI	Unemployment	HDI
$0.85523987\hat{\imath} - 0.00434867\hat{\jmath}$	$-0.13011501\hat{\imath} + 0.0006616\hat{\jmath}$	$-0.1191104\hat{\imath} + 0.01440754\hat{\jmath}$	$-0.48765016\hat{\imath} - 0.01132232\hat{\jmath}$

4. We applied these weights to the values in the evaluation matrix in order to get a weighted decision matrix $R = [t_{ij}]$:

$$t_{ij} = r_{ij} \cdot w_j, \quad i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots, n$$

5. In order to eliminate the influence of index dimension and its variation range on evaluation results it was necessary to normalize the evaluation matrix. The weighted normalized decision matrix is the $R = [r_{ij}]_{m \times n}$, which is calculated as:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}^2}}, \quad i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots, n$$

Determination of the Ideal Solution

6. For each region and each parameter within that region, we calculated the geometric distance from the parameter's ideal value. For EI, GNI, and HDI, the ideal value was the maximum value in those columns. For unemployment, the ideal value was the minimum value of the column.

$$d_{iw} = \sqrt{\sum_{j=1}^{n} (t_{ij} - t_{wj})^2}, \quad i = 1, 2, \ldots, m,$$

7. Using the same method, we calculated the geometric distance from the parameter's worst value. For EI, GNI, and HDI, a lower value was the minimum which meant for the model we used positive impact parameters. For unemployment, a higher value was worse (who wants more unemployment?) so we used negative impact parameters.

$$d_{ib} = \sqrt{\sum_{j=1}^{n}(t_{ij} - t_{bj})^2}, \quad i = 1, 2, \ldots, m$$

8. The TOPSIS score for each region was calculated:

$$\begin{aligned} s_{iw} &= d_{iw}/(d_{iw} + d_{ib}), \quad 0 \le s_{iw} \le 1, \quad i = 1, 2, \ldots, m. \\ s_{iw} &= 1 \\ s_{iw} &= 0 \\ s_{iw} &\ (i = 1, 2, \ldots, m). \end{aligned}$$

9. We fitted a linear model onto our data to project future values of our parameter using an Ordinary Least Squares Linear Regression machine learning model from scikit-learn [17]:

$$\begin{aligned} \hat{\beta} &= \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - (\sum x_i)^2} \\ \hat{\alpha} &= \overline{y} - \hat{\beta}\,\overline{x}\ , \end{aligned}$$

We estimate an arbitrary time frame of 30 years for asteroid mining to become feasible, so we project our values to 2050.

To factor in the weightage of asteroid mining on our parameters, we looked at prior recessions in commodities and precious metals prices and saw how they affected each one of our parameters. Specifically we looked at the cyclical nature of commodity prices during economic booms and recessions. We settled on analyzing worldwide commodity prices during the financial crisis and analyzed the changes in our parmater values during the period of 2008-2010 [4]. Finally, we computed the change in our parameter values from those periods and factored that into the linear regression to create a final data point for each parameter in 2050:

2.2 Result of the Model

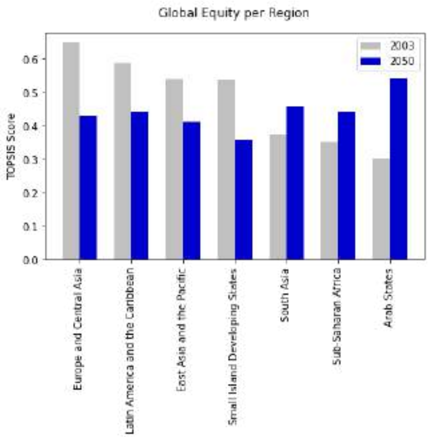
Region	Education	GNI	Unemployment	HDI
Arab States	0.800142	1.995793	7.675359	0.638233
East Asia and the Pacific	0.892229	2.359817	5.440953	0.966858
Europe and Central Asia	0.948446	2.555877	11.611373	0.926708
Latin America and the Caribbean	0.890965	2.053669	7.354624	0.893267
South Asia	0.781923	0.966896	4.498334	0.834905
Sub-Saharan Africa	0.890965	2.053669	7.354624	0.893267
Small Island Developing States	0.805805	2.587518	5.416312	0.859274

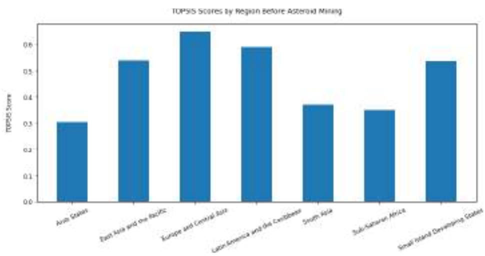
The data above represents the equity of each region as given by the parameters averaged over 28 years from 1991 to 2019. This data gave us a good sense of regional global.

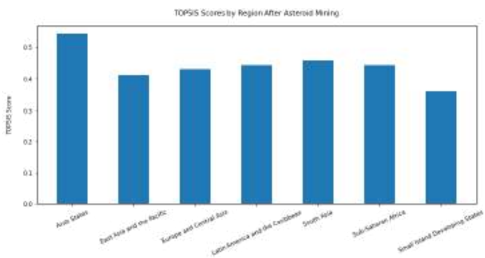
Using a linear regression model our paremeters were projected into 2050 to examine the impact of asteriod mining on equity. These future value parameters were then fed into the TOPSIS model to see what equity scores would look like after asteroid mining:

Region	TOPSIS Score
Arab States	0.543386
East Asia and the Pacific	0.412571
Europe and Central Asia	0.430158
Latin America and the Caribbean	0.442912
South Asia	0.458276
Sub-Saharan Africa	0.442912
Small Island Developing States	0.358697

When we compare the TOPSIS values before and after asteroid mining, we can see that the equity values for the regions become closer to each other:



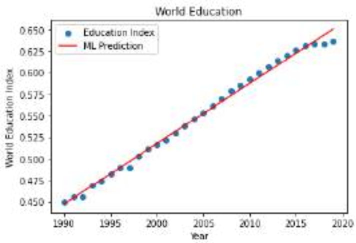


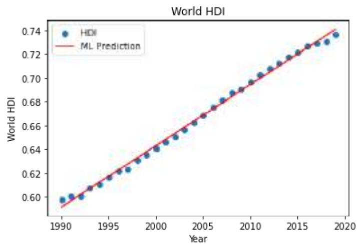


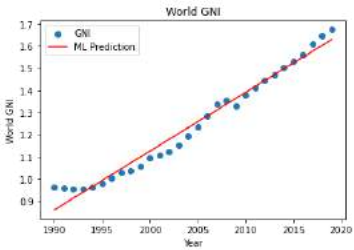
Given our definition of global equity and the trend shown in the above graphs, we conclude that asteroid mining would result in an increase in global equity.

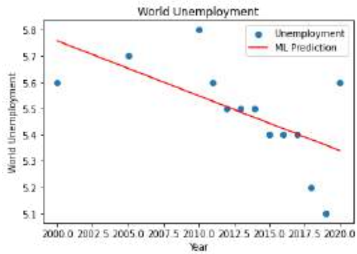
3.3 Model Visualization

World Regression Models

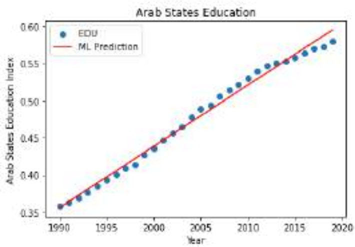


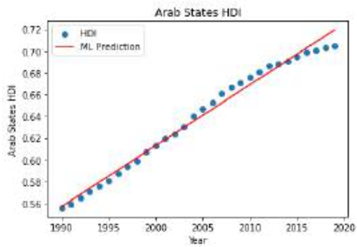


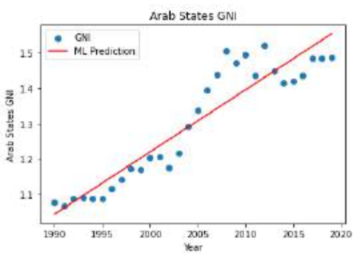


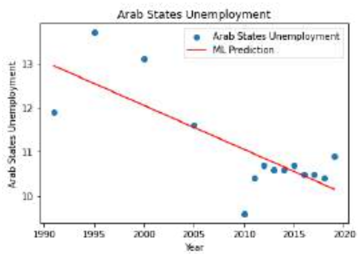


Arab States Regression Models

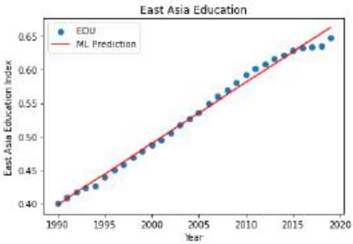


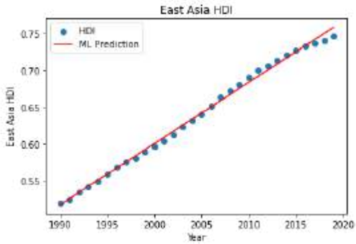


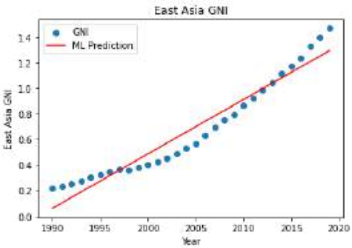


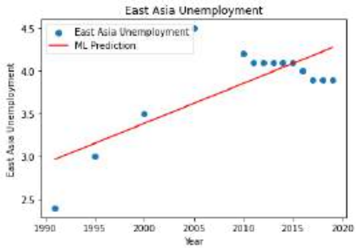


East Asia Regression Models

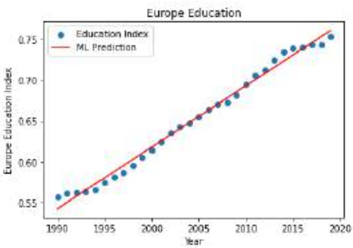


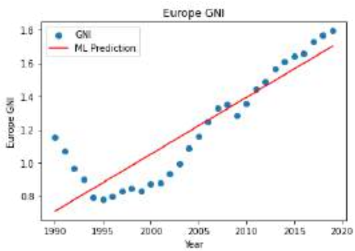


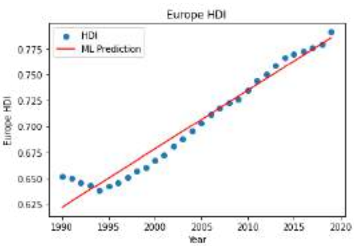


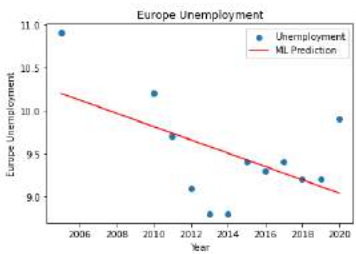


Europe Regression Models

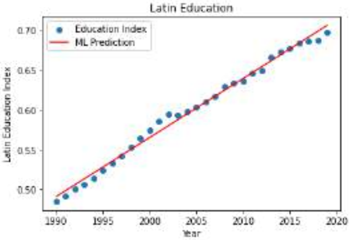


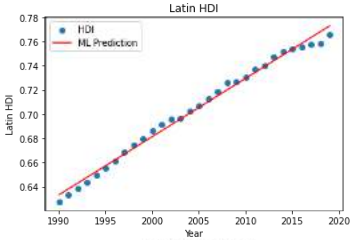


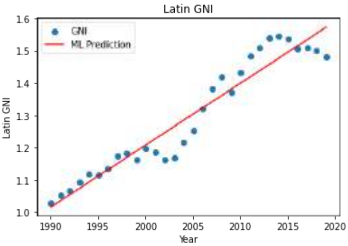


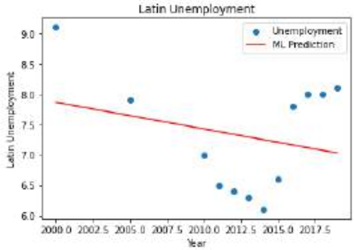


Latin Regression Models

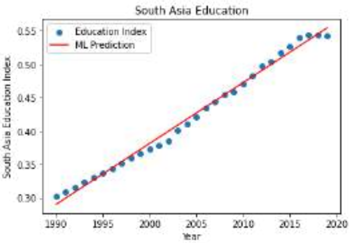


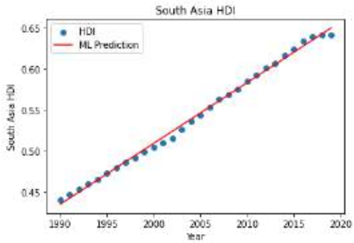


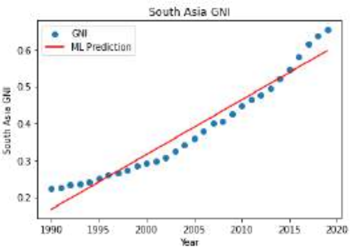


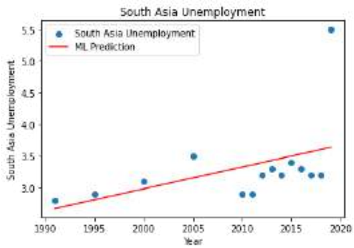


South Asia Regression Models

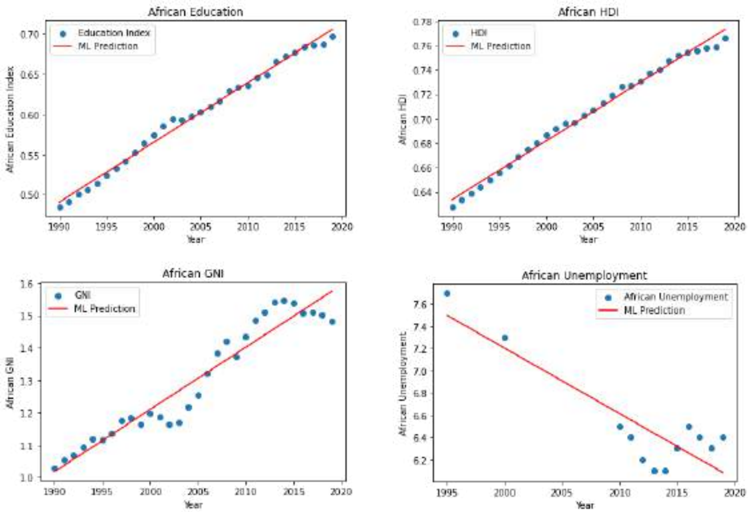




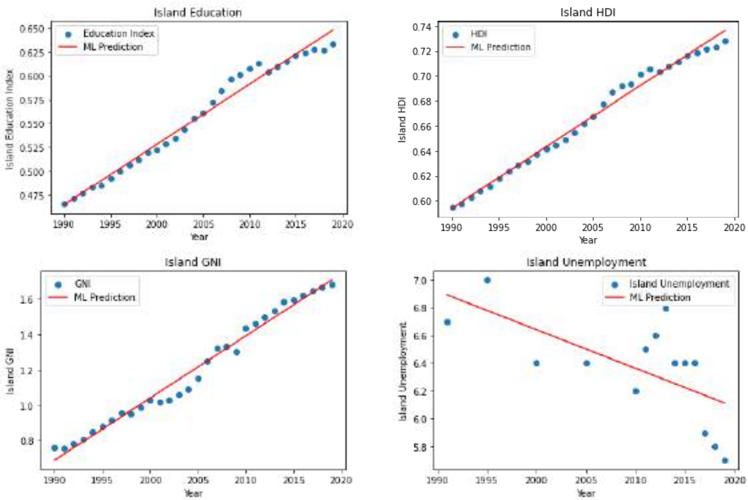




Africa



Island States



3 Recommendation to the United Nations

To Antonio Guterres, Secretary-General of the United Nations:

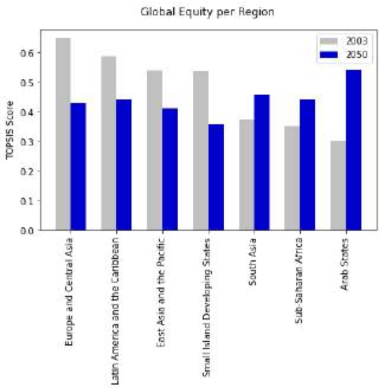
After performing a regional analysis of different factors impacting global equity, creating and evaluating equity scores, and comparing them to future equity scores, we can confidently state that asteroid mining can be used to improve global equity if implemented responsibly. Historically mining has played a role in the economic development of many countries; if done responsibly, it can be a catalyst for social growth in developing countries such as emerging economies in Sub-Saharan Africa and South Asia [9].

Asteroid mining will likely be a privatized and monopolistic business with a “finders-keepers” claim of sovereignty on resources extracted. The Outer Space Treaty (OST) currently does not allow for national appropriation of outer space, meaning that even if private corporations were not the only group with the financial capabilities to mine asteroids, legal repercussions from the OST prevent state-sponsored mining or exploration of asteroids [16]. In this current framework, asteroid mining will likely become a monopolistic enterprise, with profits going back exclusively toward the monopolistic corporation.

We agree with the current legal framework of the OST because it prevents state weaponization of outer space. In a sense, we sponsor creating a monopolistic private business to carry out asteroid mining simply because it would be easier to regulate. The most equitable policy to be implemented would be a community development agreement carried out between the United Nations and this corporation. Specifics of the agreement would place a tariff on the corporation and a clause on the disbursement of materials mined from the asteroid, emphasizing emerging economies. This is to encourage international investment in these developing nations, which can then be used to diversify economic activity and improve economic development [15].

4 Conclusion

After examing present and projected regional equity scores we can see from our TOPSIS model and the bar graph that equity socres become similar implying that global equity will increase if asteroid mining were to become feasible.



4.1 Strengths

The primary strength of our analysis is our use of the TOPSIS model to quantify global equity. The TOPSIS model is useful for analyzing disparate criteria in a compensatory manner and producing a number that represents the quality of the alternative based on the criteria. In our case, the TOPSIS model gave us a straightforward way to quantify global equity for each region according to our parameters: education, GNI, unemployment, and HDI.

Another strength of our analysis is our use of data from past commodity recessions to predict how asteroid mining would affect global equity. By factoring in the changes of our data from the financial crisis we were able to quantitatively predict how global equity would change using our TOPSIS model.

4.2 Weaknesses

Weaknesses in our methodology mostly come from a lack of data values for the North American and Australian regions. Our data for unemployment percentages was also limited. Due to the sparsity of the data our regression coefficnet's for the linear regression model If we were to do it again, finding more extensive data to feed into the model would give us a better sense of how mining could affect global equity. In addition to limited data, the parameters we considered when calculating our equity scores are subjective and may not necessarily be the best considerations for defining global equity.

4.3 Assumptions

Assumptions when using this model were that our dataset was monotonically increasing or decreasing and that the scatter plots created were linear. Our assumptions were mostly justified when we plotted our data values over time. The only problem was with the unemployment data which we resolved by slicing the dataframe to create a linear model . We also assume a time for when asteroid mining will be common enough to justify an impact in our parameters. Research is split on an exact time frame so we choose an arbitrary value of 2050.

Appendices

TOPSIS Code

Language: Python

```
import numpy as np


class Topsis:
    """ Define a TOPSIS decision making process
    TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution)
    chooses and ranks alternatives of shortest distance from the ideal solution
    """
    C = None
    optimum_choice = None

    def __init__(self, a, w, I):
        """ Initialise topsis object with alternatives (a), weighting (w),
        and benefit/cost indicator (i). Validate the user input for correct
        dimensions etc.
        :param np.ndarray a: A 2D array of shape (J,n)
        :param np.ndarray w: A 1D array of shape (J)
        :param np.ndarray I: A 1D array of shape (n)
        """
        # Decision Matrix
        self.a = np.array(a, dtype=np.float).T
        assert len(self.a.shape) == 2, "Decision matrix a must be 2D"

        # Number of alternatives, aspects
        (self.n, self.J) = self.a.shape

        # Weight matrix
        self.w = np.array(w, dtype=np.float)
        assert len(self.w.shape) == 1, "Weights array must be 1D"
        assert self.w.size == self.n, "Weights array wrong length, " + \
                                      "should be of length {}".format(self.n)

        # Normalise weights to 1
        self.w = self.w/sum(self.w)

        # Benefit (True) or Cost (False) criteria?
        self.I = np.array(I, dtype=np.int8)
        assert len(self.I.shape) == 1, "Criterion array must be 1D"
        assert len(self.I) == self.n, "Criterion array wrong length, " + \
                                      "should be of length {}".format(self.n)

        # Initialise best/worst alternatives lists
        ab, aw = np.zeros(self.n), np.zeros(self.n)
```

```
def __repr__(self):
    """ What to print when the object is called?
    """
    # If optimum choice not yet calculated, start the calculation!
    if self.optimum_choice == None:
        self.calc()
    opt_idx = self.optimum_choice
    return 'Best alternative\na[{}]: {}'.format(opt_idx, self.a[:, opt_idx])


def step1(self):
    """ TOPSIS Step 1
    Calculate the normalised decision matrix (self.r)
    """
    self.r = self.a/np.array(np.linalg.norm(self.a, axis=1)[:, np.newaxis])
    return


def step2(self):
    """ TOPSIS Step 2
    Calculate the weighted normalised decision matrix
    Two transposes required so that indices are multiplied correctly:
    """
    self.v = (self.w * self.r.T).T
    return


def step3(self):
    """ TOPSIS Step 3
    Determine the ideal and negative-ideal solutions
    I[i] defines i as a member of the benefit criteria (True) or the cost
    criteria (False)
    """
    # Calcualte ideal/negative ideals
    self.ab = np.max(self.v, axis=1) * self.I + \
            np.min(self.v, axis=1) * (1 - self.I)
    self.aw = np.max(self.v, axis=1) * (1 - self.I) +  \
            np.min(self.v, axis=1) * self.I
    return

def step4(self):
    """ TOPSIS Step 4
    Calculate the separation measures, n-dimensional Euclidean distance
    """
    # Create two n long arrays containing Eculidean distances
    # Save the ideal and negative-ideal solutions
    self.db = np.linalg.norm(self.v - self.ab[:,np.newaxis], axis=0)
    self.dw = np.linalg.norm(self.v - self.aw[:,np.newaxis], axis=0)
    return
```

```
def step5(self):
        """ TOPSIS Step 5 & 6
        Calculate the relative closeness to the ideal solution, then rank the
        preference order
        """
        # Ignore division by zero errors
        #np.seterr(all='ignore')
        # Find relative closeness
        self.C = self.dw / (self.dw + self.db)
        self.optimum_choice = self.C.argsort()[-1]
        return


    def calc(self):
        """ TOPSIS Calculations
        This can be called once the object is initialised, and is
        automatically called when a representation of topsis is
        needed (eg. print(topsis(matrix, weights, I)). This calls each step in
        TOPSIS algorithm and stores calcultions in self.
        The optimum alternatives index (starting at 0) is saved in
        self.optimum_choice
        """
        self.step1()
        self.step2()
        self.step3()
        self.step4()
        self.step5()
        return
```

Linear Regression Model Fitting

Language: Python

```
def futurePredictorValue(data_frame, y_label, graph_title, legend_title,
year_to_predict):
    """
    Linear Regessor to find future global equity in the year 2050
    """

    data = data_frame.T.loc[:, '1990':]
    data.insert(1, "Year", [1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998,
1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012,
2013, 2014, 2015, 2016, 2017, 2018, 2019])

    # values converts it into a numpy array
    Y = data.iloc[:, 0].values.reshape(-1, 1)

    # -1 means that calculate the dimension of rows, but have 1 column
    X = data.iloc[0:, 1].values.reshape(-1, 1)

    linear_regressor = LinearRegression()  # create object for the class
    linear_regressor.fit(X, Y)  # perform linear regression
    Y_pred = linear_regressor.predict(X)  # make predictions

    predicted_value = year_to_predict * linear_regressor.coef_
                      + linear_regressor.intercept_

    variable_in_2003 = 2003 * linear_regressor.coef_ + linear_regressor.intercept_
    variable_in_2009 = 2009 * linear_regressor.coef_ + linear_regressor.intercept_
    predicted_delta_during_mining = variable_in_2009 - variable_in_2003

    final_prediction = predicted_value[0][0] - world_delta_in_mining[0][0]

    return final_prediction
```

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