An Evolutionary Economic Model for Predicting the Equity of Asteroid Mining

Davidson Cheng, Yinting Zhong

Department of Mathematics and Computer Science, Colorado College

March 12th, 2022

Problem Statement and Dissection

Problem: When asteroid mining becomes a reality, how will it impact global equity?

- What is global equity and how can we measure it?
- What would asteroid mining look like if it is feasible some day?
- How will the answer to the question above affect equity?
- What policy can we expect to be put in place in order to promote equity, and how effective can they be?

General Definition of Equity

General Definition

- “the quality of being fair"
- “allocating those resources and opportunities in a way that supports a goal of similar outcomes"
- In general, people from all backgrounds should have similar opportunity in participating and succeeding in some industry/field.

Mathematical Definition

The measurement for equity of an industry/field needs to be based on some feature of the population (such as gender, age, sextual orientation, ...) We would like to see whether the distribution of the population in this feature matches that of the industry/field.

Kullback-Leibler (KL) Divergence

KL Divergence

Definition

Given some distribution A and B on the same discrete probability space χ, the KL-Divergence of B from A is defined as

$$KL(A,B) = \sum_{x \in \chi} A(x) log_2(\frac{A(x)}{B(x)}).$$

Note: The KL-Divergence measures how different two distributions are from each other, high KL-Divergence implies two very different distributions.

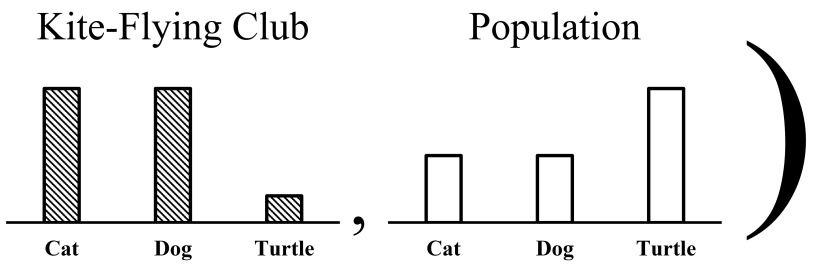
Diversity Metric

The diversity metric is a measurement for the inclusiveness of an industry or field. When an industry is diverse, we expect it to be a fair representation of the overall population.

Definition

The diversity metric of a group over some feature is the KL divergence from the distribution of the overall population to the group's distribution.

$$KL\Big(\quad , \quad\Big)$$



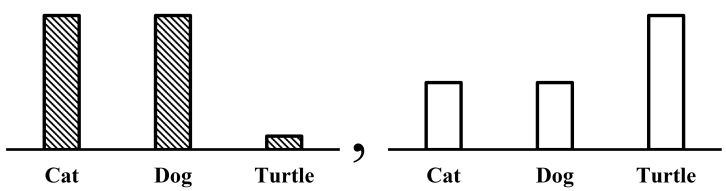
Success Metric

The success metric can be applied to an industry when there is a quantitative measurement of an individual's excellence within that industry.

Definition

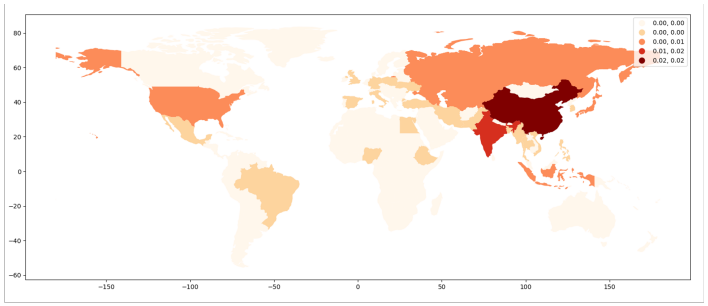
The success metric of a group over some feature is the KL divergence from the "weighted" distribution of "quantified success" of a group to that of the overall population.

$$KL\Big(\text{Kite-Flying Club}, \text{Population}\Big)$$

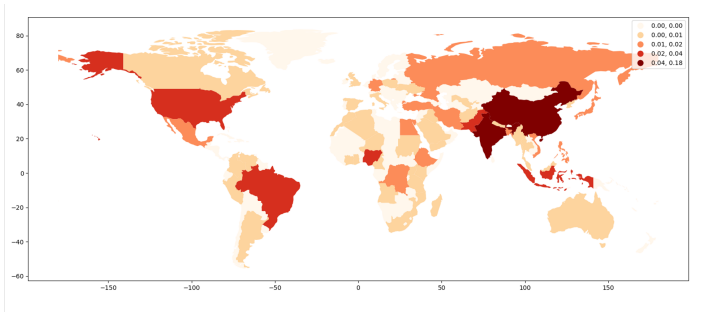


Empirical Validation

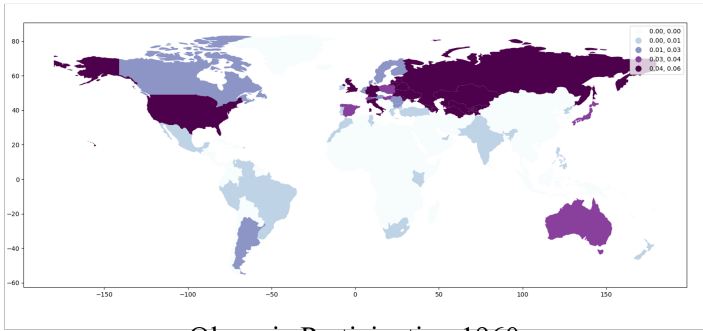
Geographical equity of the Olympics



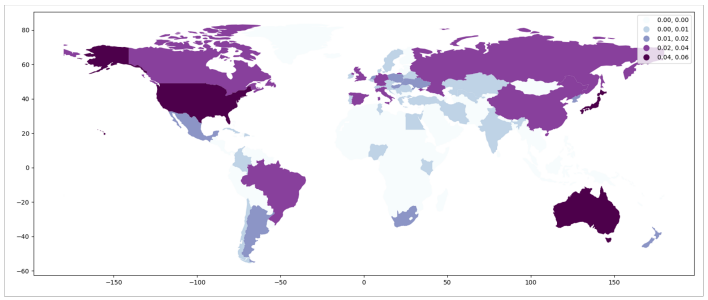
Population 1960



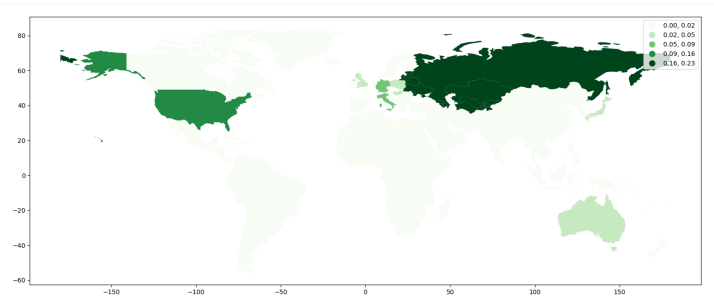
Population 2020



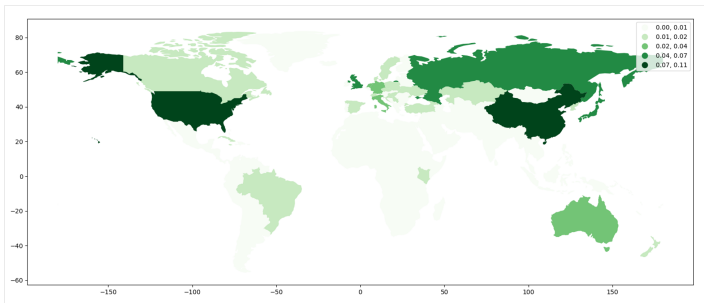
Olympic Participation 1960



Olympic Participation 2021



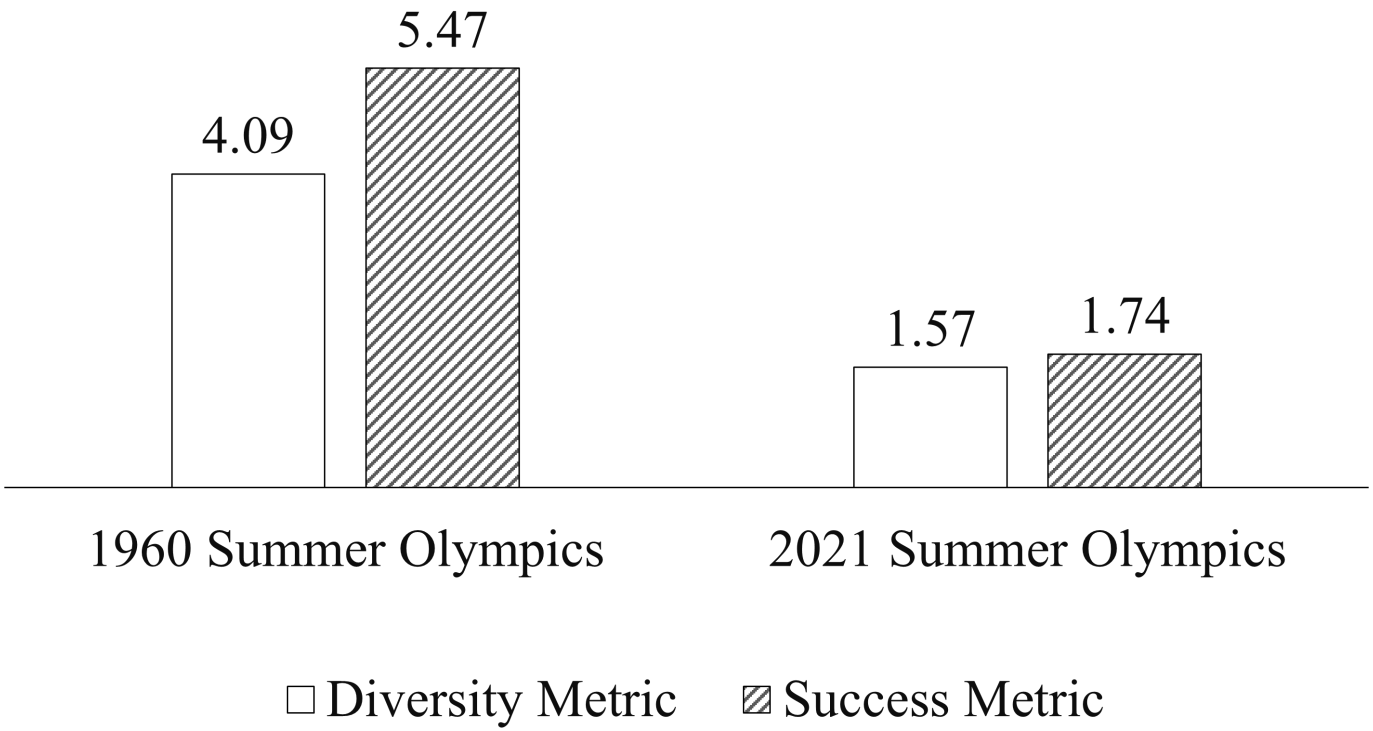
Olympic Medal Count 1960



Olympic Medal Count 2021

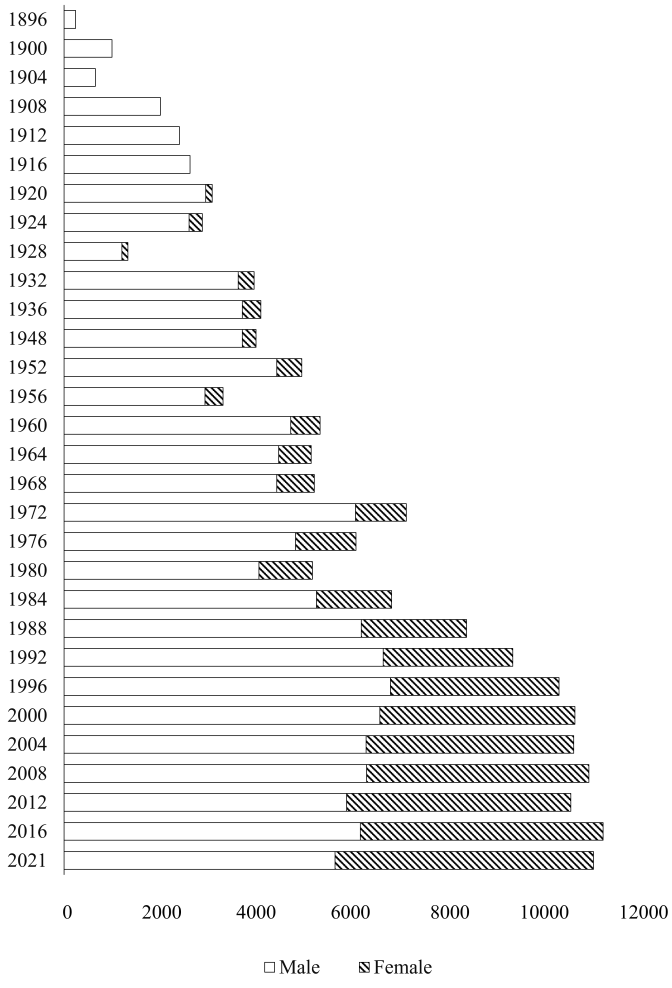
Empirical Validation

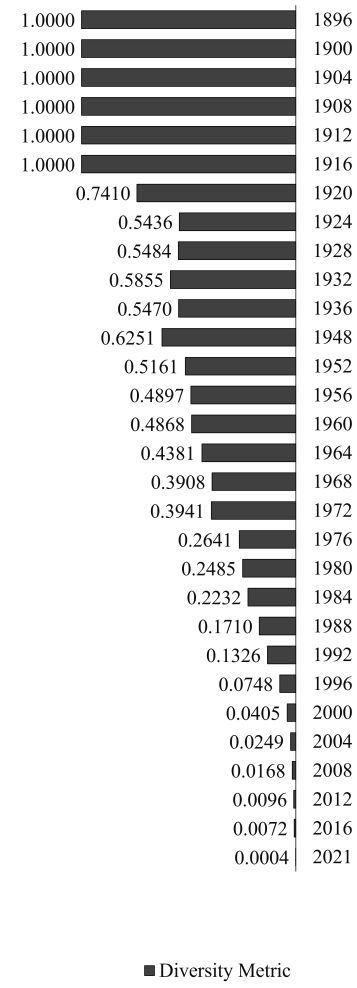
Geographical equity of the Olympics



Empirical Validation

Gender equity of the Olympics

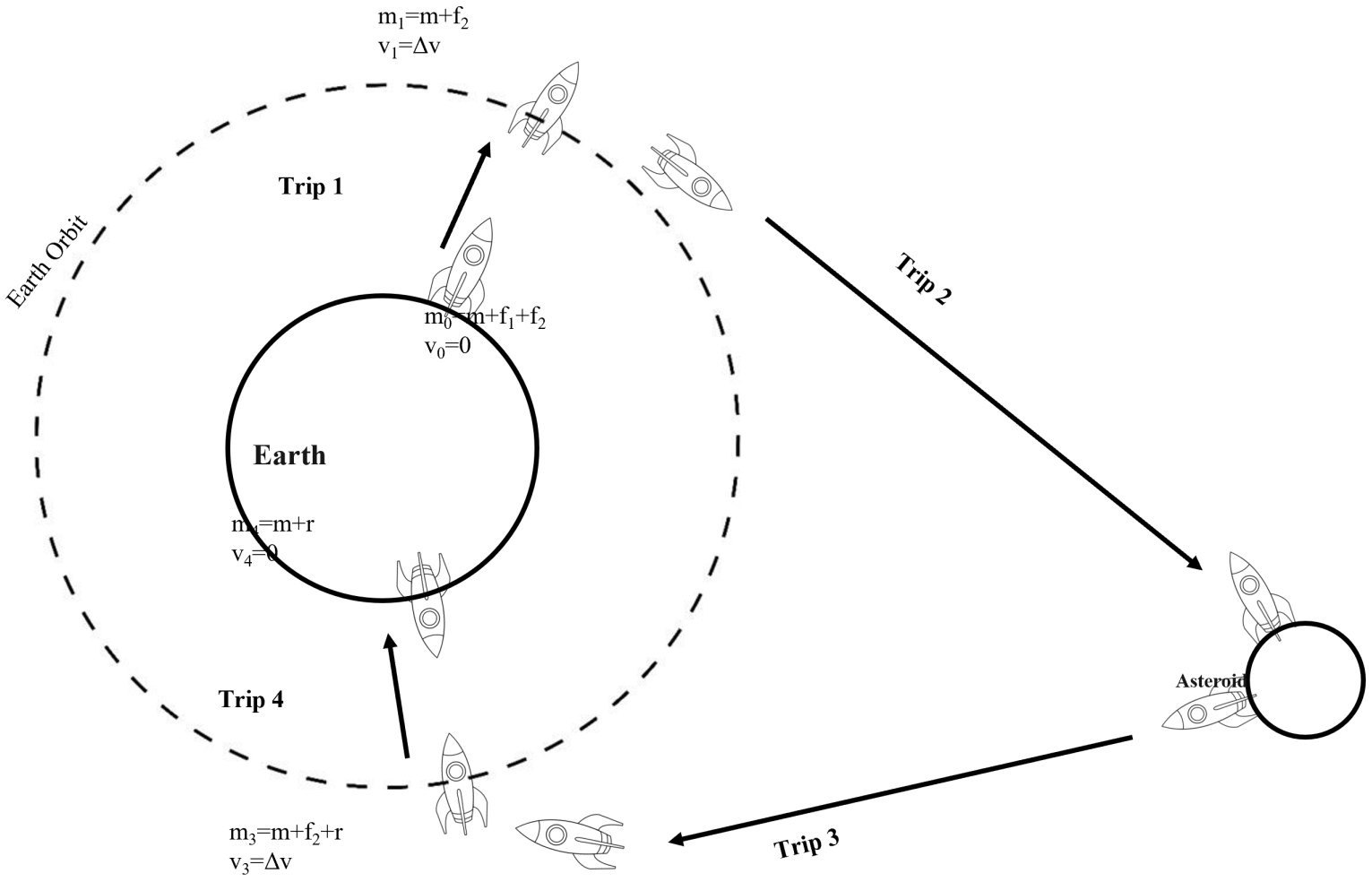




Asteroid Mining

- Determine the profitability of asteroid mining
- Accessibility of asteroid mining

Asteroid Mining



Tsiolkovsky equation

The Tsiolkovsky equation, also known as the rocket equation, is a popularly adopted model for estimating the amount of fuel needed for escaping Earth's gravitational pull. It states

$$\Delta v = v_e \ln \frac{m_0}{m_1}$$

Then the amount of fuel needed for bringing one kilogram of resource back from space can be expressed as

$$\text{fuel(kg)/resource(kg)} = e^{2(\frac{\Delta v}{v_e})} - e^{\frac{\Delta v}{v_e}} + \frac{m}{r}(e^{2(\frac{\Delta v}{v_e})} - 1)$$

Cost Effectiveness

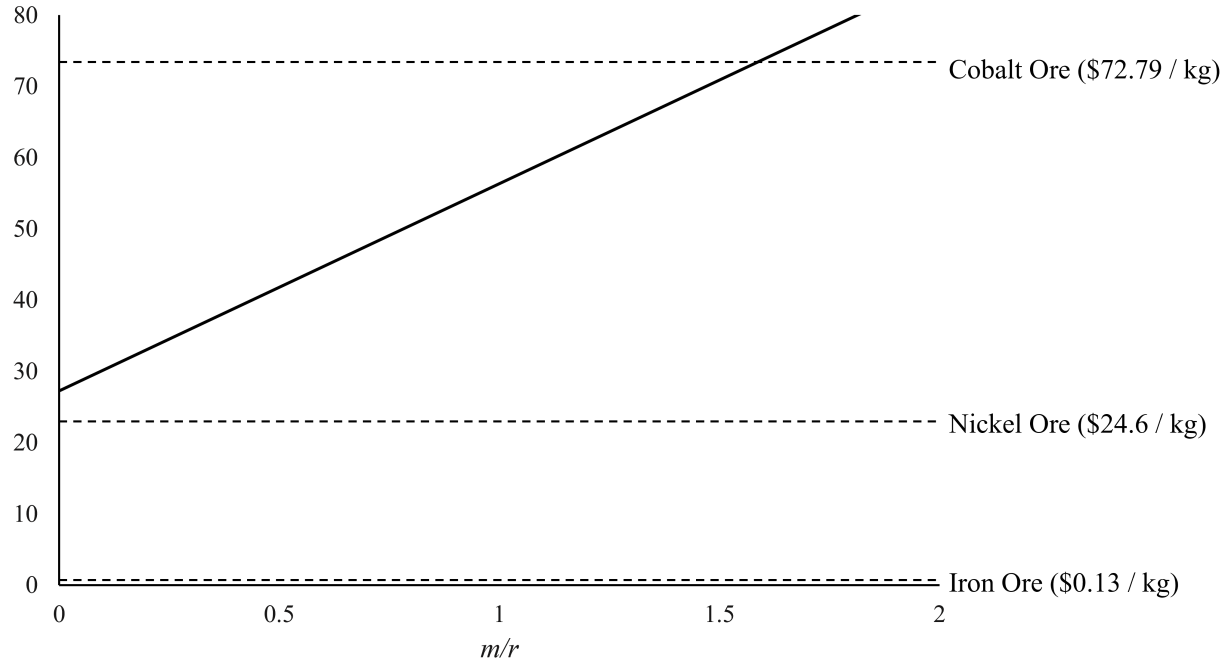
Plugging $\Delta v = 7.5$ and $v_e = 3$ into our previous equation, we get

$$\text{fuel(kg)/resource(kg)} = 136.23 + (145.41)\frac{m}{r}.$$

Current liquid gas propellants for rockets cost approximately \$0.1 per kilogram. After taking operational costs into consideration, the cost (\$) per resource can then be expressed as

$$\text{cost (\$) / resource (kg)} = 27.25 + (29.08)\frac{m}{r}.$$

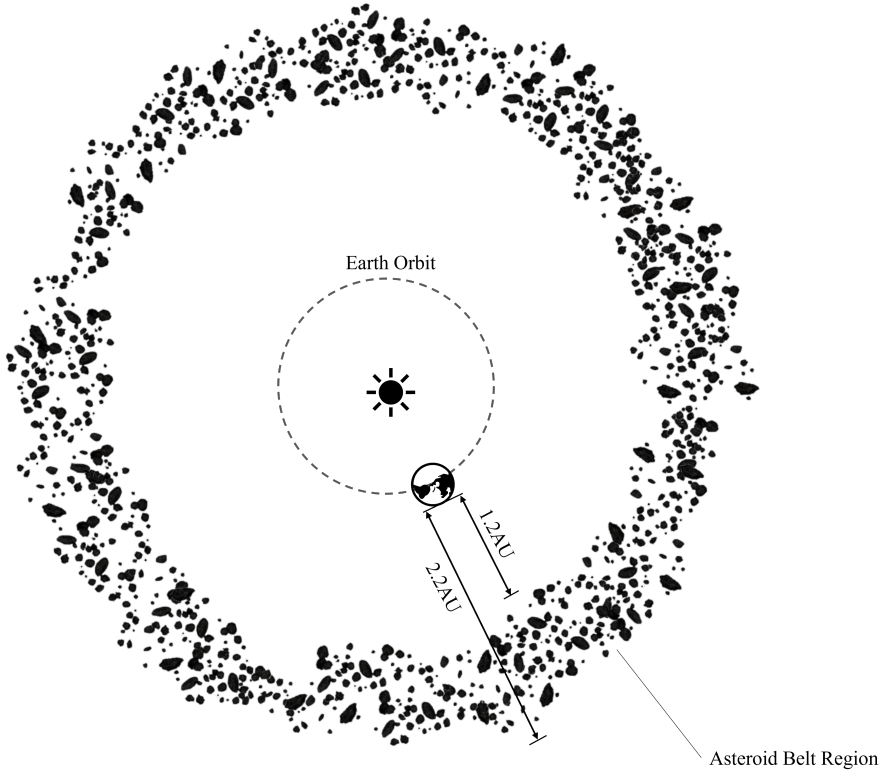
Cost Effectiveness



—Cost ($) / Mineral (kg) --- Mineral Market Price (February 2022)

$$\text{profit}(\$)/\text{resource}(\text{kg}) = 45.54 - (29.08)\frac{m}{r}.$$

Travel Time



$$\text{profit(\$)/resource(kg)/year} = \frac{45.54 - (29.08)\frac{m}{r}}{2.15}$$

Asteroid Mining and Equity

- We choose to focus on geographical equity by continets
- We use relative indices to predict how equitable asteroid mining will be

Asteroid Mining and Equity

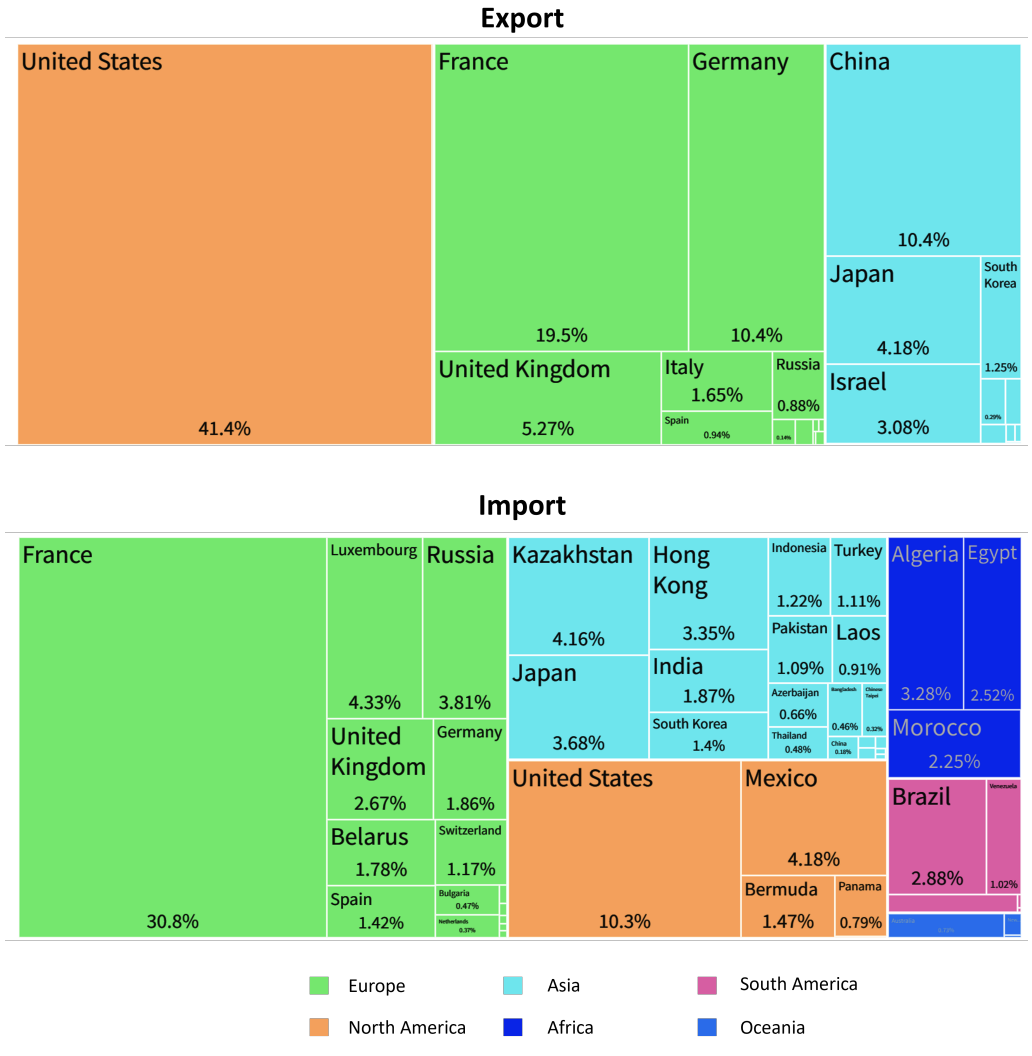
Recall

$$\text{profit(\$)/resource(kg)/year} = \frac{45.54 - (29.08)\frac{m}{r}}{2.15}$$

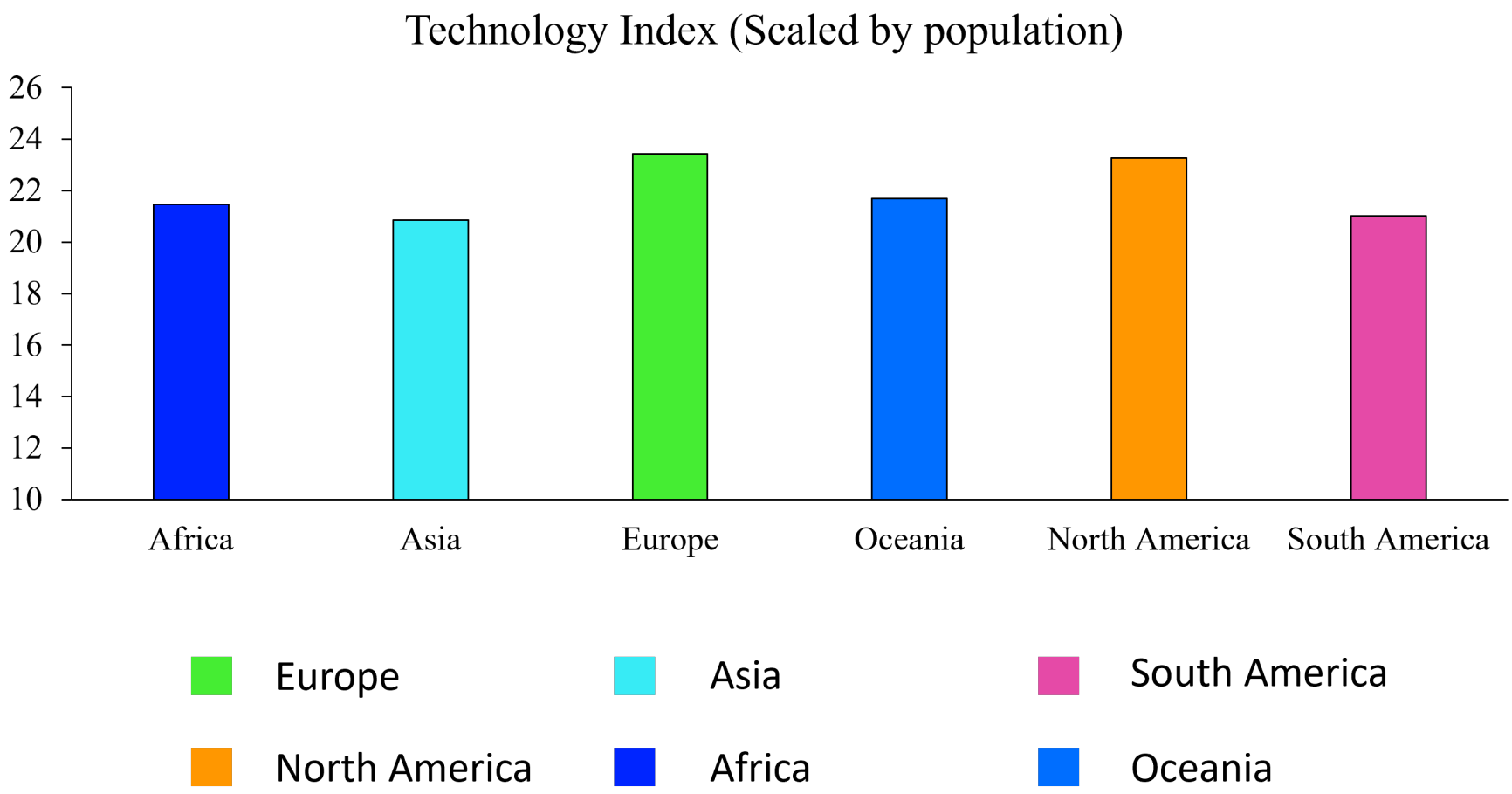
Mining Efficiency Index $= \frac{m}{r}$
Critical Value: Mining Efficiency Index $= 1.57$.

Determining Technology Index

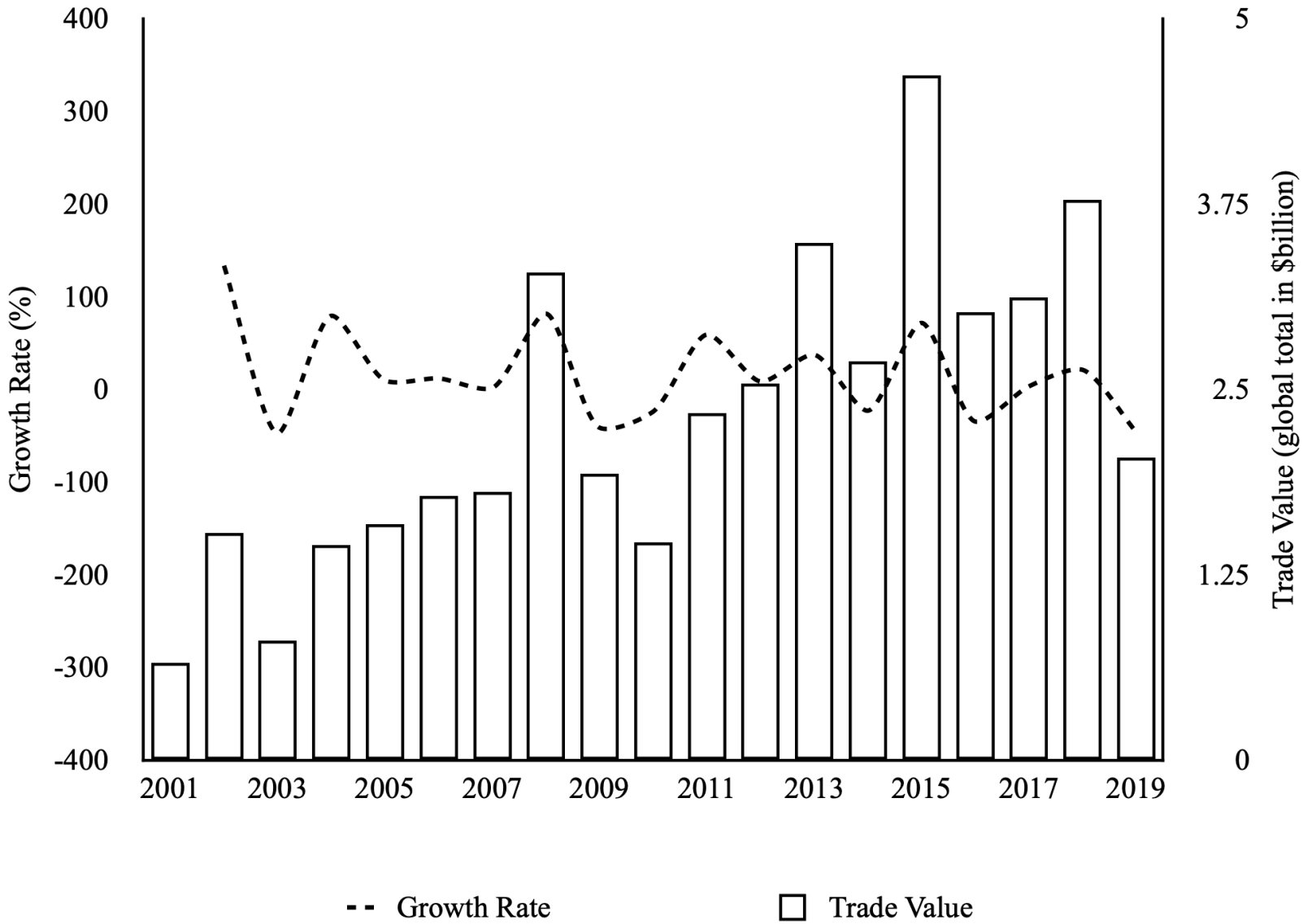
World Aerospace-related import and export between 2015 and 2019.



Determining Technology Index



Determining Technology Index



Evolutioary Economic Model

- We build a multiagent economic model to predict how the asteroid mining industry develops (every continet is treated as an agent)
- It is called “evolutionary" because it describes how different agents evolve over time
- The model contains many rounds where each round represents a year.

Evolutionary Economic Model

Year 0

Technology Index	**…**	**…**	**…**	**…**
Participation Index	**0**	**0**	**0**	**0**
Earning Index	**0**	**0**	**0**	**0**

…

Year 100

Technology Index	**…**	**…**	**…**	**…**
Participation Index	**…**	**…**	**…**	**…**
Earning Index	**…**	**…**	**…**	**…**

Participation Index

Recall

$$\text{profit(\$)/resource(kg)/year} = \frac{45.54 - (29.08)\frac{m}{r}}{2.15}$$

Mining Efficiency Index = $\frac{m}{r}$
Critical Value: Mining Efficiency Index = 1.57.

- We create a mapping from technology index to mining efficiency index, such that as technology index increases, mining efficiency decreases.
- In some given year, if the corresponding mining efficiency index is less than 1.57 for some agent, we increase the participation index by some value porportional to the population.

Earning Index

Recall

$$\text{profit(\$)/resource(kg)/year} = \frac{45.54 - (29.08)\frac{m}{r}}{2.15}$$

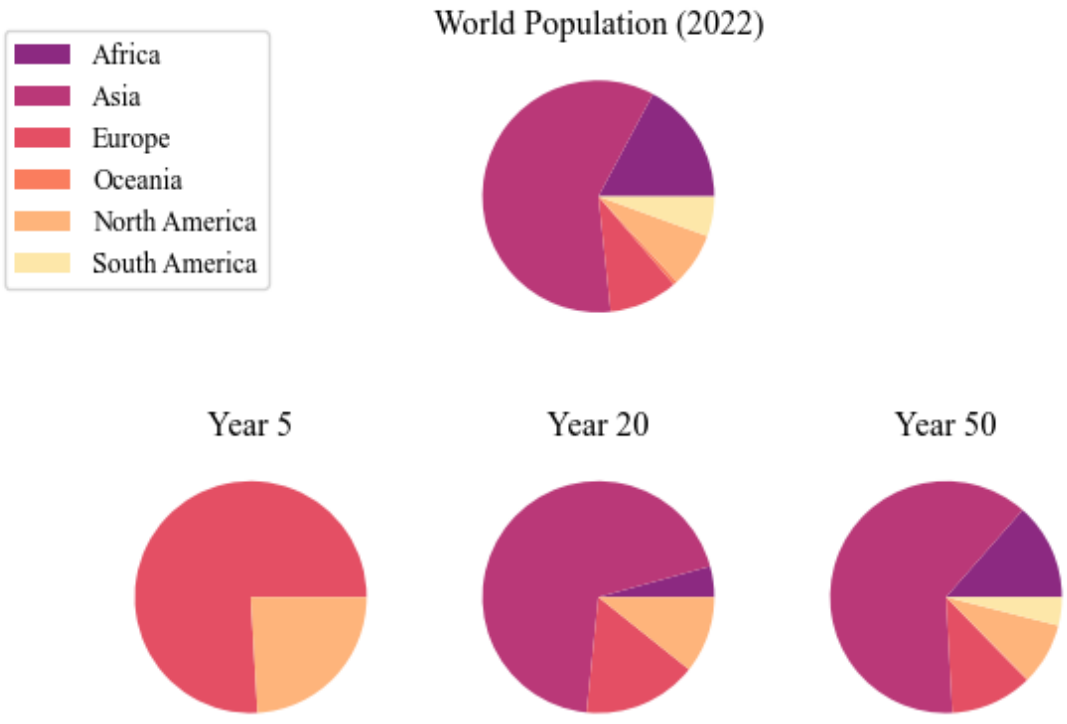
- The earning should be porportional to the participation times the above formula.
- In some given year, the earning index is increased by the participation index at that year and their profit/resource/year.

Model Outcome

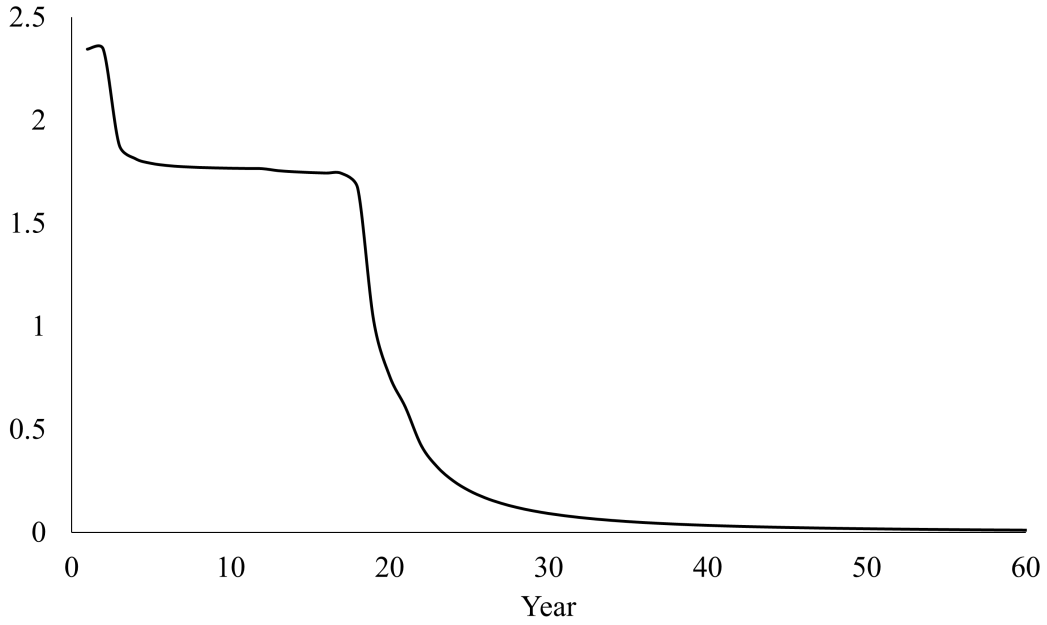
This model produces

- Relative participation in asteroid mining at a given year
- Relative earning in asteroid mining at a given year
- We can apply the aforementioned diversity metric along with the success metric with earning as the quantitative success measure.

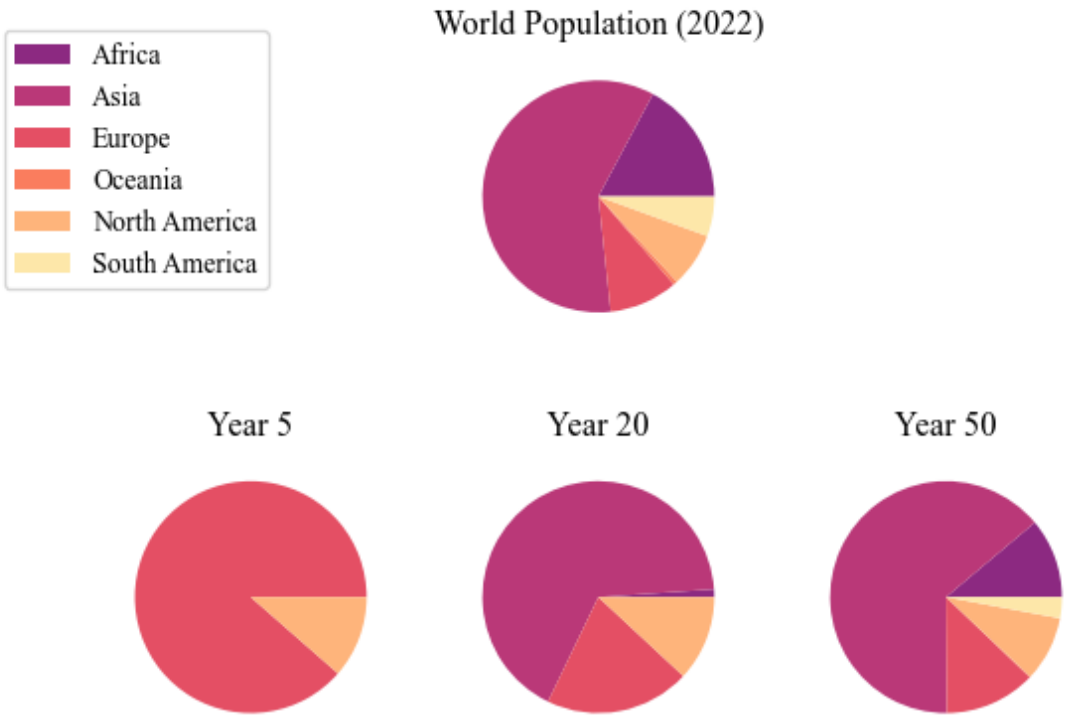
Diversity Metric Results



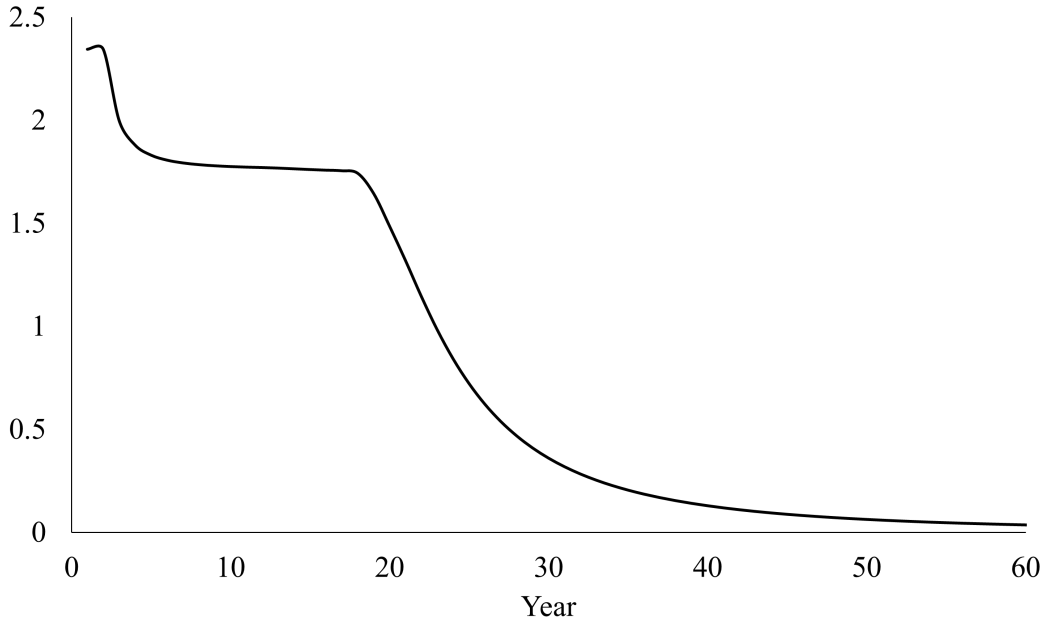
Diversity Metric Results



Success Metric Results



Success Metric Results



Policy Implications

We propose a high-to-low policy.

- The "high-to-low" policy will take a portion of the increment in technology index from the higher earner members, and distribute them to the other members evenly.
- Similar to an aid program.

Policy Implications

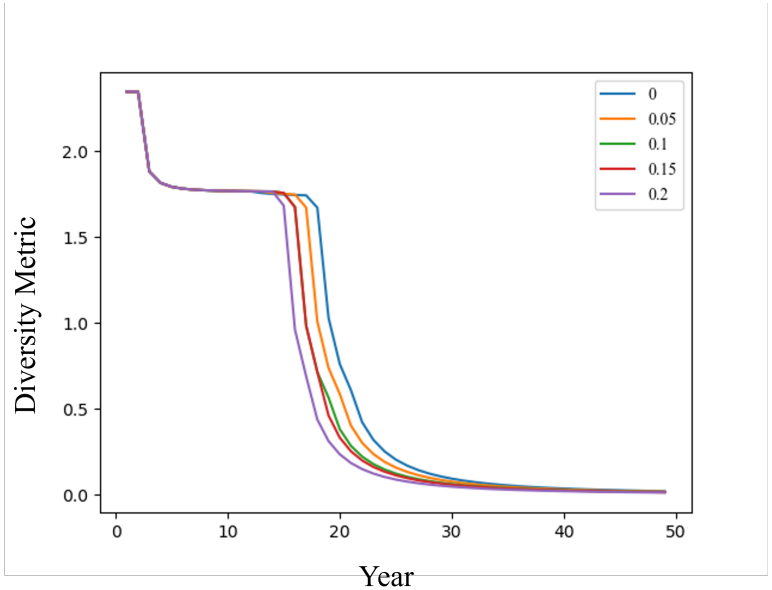
Assistance Ratio = 0.1

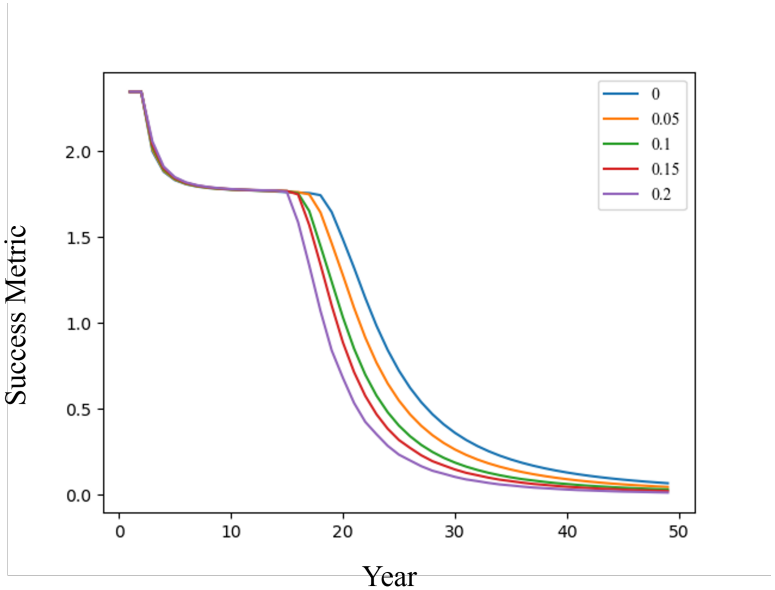
	Firm A		Firm B		Firm C		Firm D
							
Technology Index	*a*	>	*b*	>	*c*	>	*d*

Next Year

	Firm A	Firm B	Firm C	Firm D
				
Technology Index	*a + (0.9)r*	b + *(0.9)r*	*c + (1.1) r*	*d + (1.1) r*

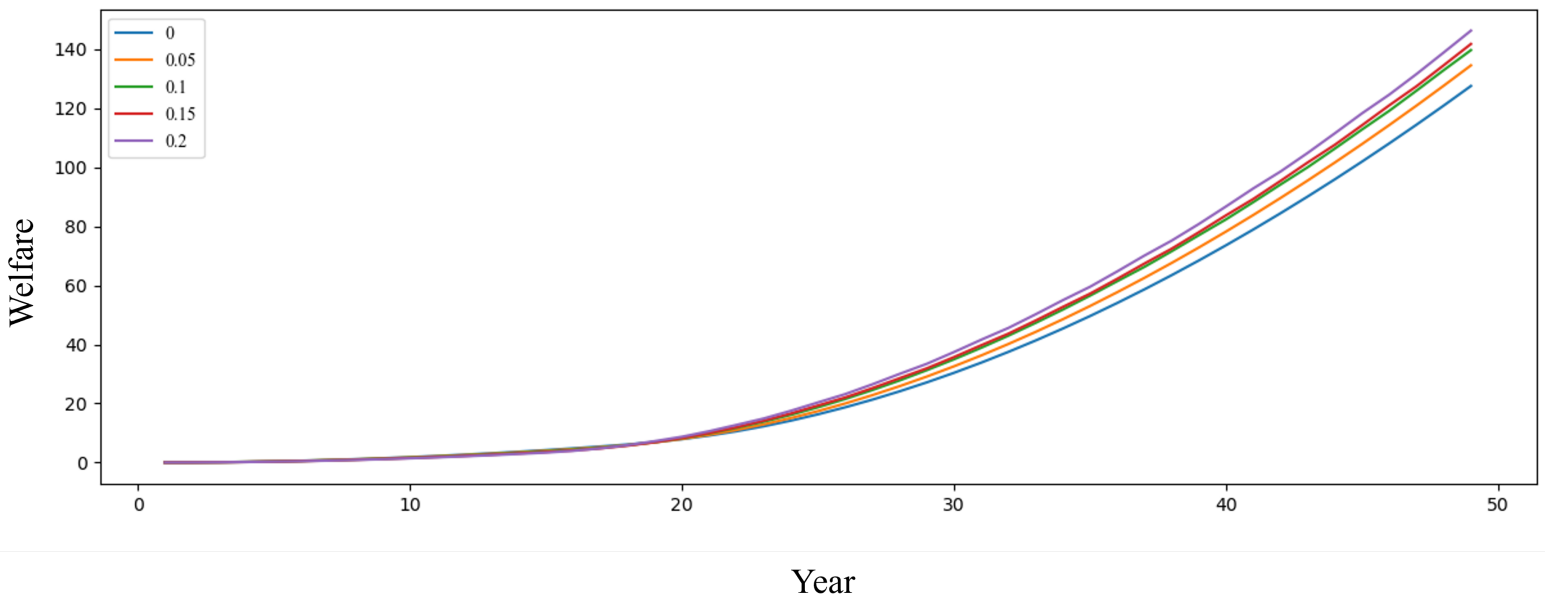
Effect of Policies





This policy allows both metrics to drop faster (achieve equity faster)

Effect of Policies



This policy increases the welfare of the entire industry.

Conclusion

In this paper, we accomplish the following things:

- Defining global equity generally and providing mathematical measurements for equity.
- Estimating the cost and profit of the asteroid mining industry.
- Developing an evolutionary model for predicting the level of equity in the asteroid mining industry at different points in the future.
- Proposing a policy that can help advance global equity in the asteroid mining industry.

Strength

- Our equity measurement model can evaluate two aspects of equity: entry opportunity and success opportunity.
- We find a policy that can promote equity while increasing welfare within the asteroid mining industry.

Weakness

- The model in the “Asteroid Mining and Equity" section assumes an equal rate of growth in population and space-related industries across the globe.
- Externalities of asteroid mining are not considered.

Thank You

Thank You! Any Questions

email: d_cheng@coloradocollege.edu