Modeling changes in the Global Petroleum Market Following The Construction of a Kra Canal

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June 3, 2024

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1 Introduction

Situated between continental Malaysia and the Indonesian island of Sumatra, the strait of Malacca is one of the world's most valuable passages for maritime transit, rivalling Panama, the Suez Canal, and the Cape of Good Hope in volume of trade routes. Among these trade routes are the imports of exports of east Asian economies such as Japan, South Korea, and China, connecting them to Indian Ocean. The straight of Malacca has proven to be the preferred choice for importing crude oil from the Persian gulf, with China importing 80% of its through this stretch.[1]

As an important route for the basis of dozens of economies, there is significant pressure to find shortcuts that could slash transit costs, as even a single digit percentage of savings would be multiplied by the US $3.5 Trillion currently passing through the strait annually. Because of this, there have been reemerging proposals for the past 4 centuries pushing the idea of a 'Kra Canal', cutting through Thailand's Kra peninsula and providing a less circumventuous route from the Indian ocean to the South China Sea.

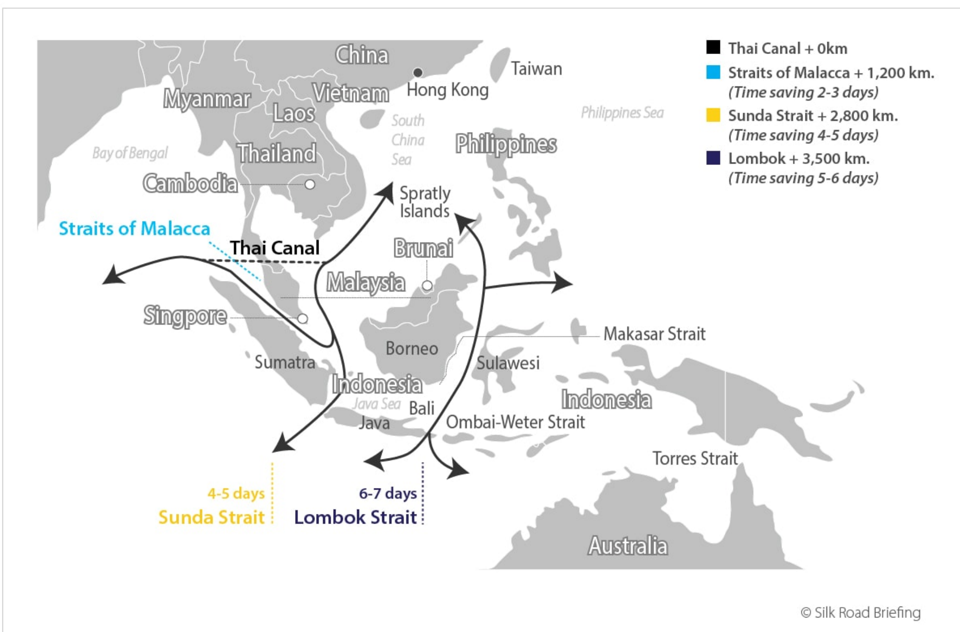

Figure 1: Malacca Strait, Thai canal, and other regional routes. Source: ASEAN Briefing

1. Thomas Dent, "The Strait of Malacca's Global Supply Chain Implications," Accessed: May 2024, *Institute for Supply Management*, November 2023, https://www.ismworld.org/supply-management-news-and-reports/news-publications/inside-supply-management-magazine/blog/2023/2023-11/the-strait-of-malaccas-global-supply-chain-implications/.

In recent years, these construction proposals have regained traction, with China a key proponent as its GDP approaches US$19 trillion and energy imports grow to scale. These proposals are far from concrete, with several locations on the Kra peninsula under consideration, and even the medium of the canal still up in the air. Many recent articles highlight the possibility of a "land bridge", essentially coast-to-coast highway that would connect ports on either side.

With so many details still uncertain about the Kra canal, it's difficult to estimate how it would effect not just economies in the region, and even more challenging to estimate the effects on global supply chains and economies. In this paper I look to investigate the direct savings that east Asian economies may see in petroleum imports, and how the new prices of supply chains could impact the choice of trade partners and economies around the world.

1.1 A Mathematical Model for Petroleum Trade

In order to assess the impact the economic impact that such a Thai canal could have, I'd first like to propose a simple model that I will use throughout the paper, which covers some of the most basic factors that are taken into consideration by the international petroleum market.

Given a set of exporting countries I and a set of importing countries J, the total global cost Z of importing crude oil can be approximated by the minimization problem:

$$\min \quad Z = \sum_{i \in I} \sum_{j \in J} x_{ij} \cdot (c_{ij} + t_{ij}) \cdot p_{ij}$$

with x_{ij} representing the volume of oil assigned to a given route from country i to country j. As the goal of this optimization is to minimize cost, three sources of cost have been included in my model. c_{ij} is the simple transport cost, calculated by the trade route distance times the cost per distance of that transport method. Other non-transport costs are represented by t_{ij}, and the goal of this variable is to catch more abstract measures such as tariffs and free trade-agreements that may additionally affect import decisions. Finally, a variable p_{ij} acts as a penalization factor for over-reliance on one specific country for imports according to the formula:

$$p_{ij} = (1.01)^{\max\left(0, \frac{x_{ij}}{\sum_{i \in I} x_{ij}} - \alpha\right) \times 100} \qquad \forall i \in I, j \in J$$

In the real world, diversification of petroleum imports is often motivated by both national governments and private enterprises seeking to strike a balance between cutting costs while protecting energy security from volatile markets. Here, this diversification penalty occurs when trade from country i to j makes up more than α percent of country j's oil imports, raising p_{ij} by whatever amount this threshold has been passed by.

Restrictions in the model include production and demand capacities, with the sum of each country's imports and exports fixed at some values D and L, respectively:

$$\sum_{i \in I} x_{ij} = D_j \quad \forall j \in J$$

$$\sum_{j \in J} x_{ij} = L_i \quad \forall i \in I$$

Traded quantities and prices of all types are constrained to real non-negative numbers:

$$x_{ij}, c_{ij}, p_{ij} \geq 0 \quad \forall i \in I, j \in J$$

This optimization problem with variable vector x_ij and parameters c_{ij}, t_{ij}, p_{ij}, and α computes in its double integral the total cost of all trade routes between all countries. As one can see, solving for the optimal trade routes in a hypothetical scenario requires the knowledge of quite a few parameters. Values of c_{ij} can be estimated in a way that I will discuss in more detail in the next section, but the parameters of t_{ij} α are less intuitive. As a result, the approach for applying this model to a set of trade routes modified by the construction of a canal can be summarized by two steps:

1. Using current trade route distances, infer the values of p_{ij} and α that would result in the current trade volumes x_ij being optimal by the objective function Z.

2. Once solved for p_{ij} and α, modify transport costs c_{ij} to reflect the construction of the Thai canal and solve again for x_{ij}

2 Data Used

For obtaining accurate information on the current maritime trade routes, I used distances as calculated by the Searoutes API,[2] which provides route distances from one port to another. For simplicity's sake, countries were reduced down to one representative port that all imports and exports would travel through. Some countries which span multiple coastlines may have two ports entered in the model, and in this case these countries ended up being Russia and the United States. With this API, all possible routes between an given country and another country, and a distance matrix was generated which stores the shortest distance for a commercial freighter to get from country i to country j. Using this to obtain my distance matrix for pre-canal values, post-canal searoute distances will also be needed. Estimates seemingly unanimously agree on 1200 km as the distance that will be cut for trade routes passing through the strait of Malacca, so for my post-canal distance matrix I simply subtracated 1200 km[3] from all routes taking this path.

Because I will be solving for other costs t_{ij} and p_{ij} as a function of transit cost c_{ij}, this allows flexibility in choosing any currency, and for computational effectiveness, I'll simply using a fixed cost-rate that converts these distances to a unitary cost matrix with a linear relationship between cost and distance.

Required specifically to solve for the parameters c_{ij} and α in step 1 are the current volumes of crude oil trade between countries. For this, CEPII's[4] yearly database of international trade volume at the product level, the BACI database, will be used. From this database, I will use the 2022 volumes of product code 270900: "Oils: petroleum oils and oils obtained from bituminous minerals, crude". These volumes are referenced in millions of tons.

Due to computational restrictions discussed more in later sections, only 10 countries are able to be fitted to the model at a time. To try and still maintain a representative profil of the global economy, I wanted to include key economies in the crude oil sector, countries that may benefit from the Thai canal, and a few countries with a variety of geographic locations and political ties. The 10 countries I decided to include ended up being: United Arab Emirates, Brasil, Iraq, USA, South Korea, Saudi Arabia, India, Spain, Thailand, and Russia. Unfortunately the BACI database had little information on China's petroleum imports, but hopefully we can use Thailand and South Korea's to guage how petroleum-importing economies of east Asia in general will be affected.

2. SeaRoutes, "https://app.searoutes.com," Accessed: May 2024, 2023, accessed April 15, 2024, https://www.searoutes.com.

3. N. S. F. Abdul Rahman, N. H. Mohd Salleh, A. F. Ahmad Najib, et al., "A Descriptive Method for Analysing the Kra Canal Decision on Maritime Business Patterns in Malaysia," *Journal of Shipping and Trade* 1, no. 13 (2016), accessed March 19, 2024, https://doi.org/10.1186/s41072-016-0016-0, https://doi.org/10.1186/s41072-016-0016-0.

4. Centre d'Études Prospectives et d'Informations Internationales, "BACI," Accessed: May 2024, 2023, accessed April 15, 2024, https://www.searoutes.com.

3 Methodology

Although the mathematical model shown earlier isn't necessarily complex in terms of number of restrictions, the calculation of some variables, particularly p_{ij} contains a variety of exponential, fractional, and boolean functions that can result in non-convexity and difficulty for many solvers to optimize. For this reason, I opted to use Pyomo with the 'SNOPT' solver developed by the team at UCSD.[5] Because the educational license restricts solvers to 300 variables, I selected the ten countries mentioned in the previous section.

The first step, formulated in section 1.1, is to use current data to estimate values of t_{ij} and α. This essentially results in solving a feasibility problem with the same objective function and restrictions written in the formulation. The only additional measure is to include some loss function to ensure that the estimated values x_{ij} are as close as possible to the real-world values x^*_{ij}. Here I use mean squared error:

$$\min \quad \text{MSE} = \frac{1}{n} \sum_{i=1}^{n} \sum_{j=1}^{n} (x_{ij} - x^*_{ij})^2$$

Resulting in the following values of t_{ij} for each pair of countries (paths not shown were set to $p = 0$):

```
1  ('AE', 'US'): 0.004517881547224075,
2  ('AE', 'ES'): 1.3860375711680937,
3  ('BR', 'IN'): 4.036811148222342,
4  ('BR', 'TH'): 0.0027623557049477688,
5  ('IQ', 'KR'): 0.013203705841342929,
6  ('KR', 'IN'): 0.29020624856309746,
7  ('KR', 'TH'): 0.3796051516564371,
8  ('IN', 'BR'): 0.0034285713767209 5,
9  ('ES', 'BR'): 0.1729522394536355,
10 ('ES', 'IN'): 0.9517362776185481,
11 ('ES', 'TH'): 0.44823457524943255,
12 ('RU', 'BR'): 0.37137091458234234,
13 ('RU', 'US'): 0.8805049527878073,
14 ('RU', 'IN'): 0.15618438350573519,
15 ('RU', 'ES'): 2.750889300841361,
16 ('RU', 'TH'): 0.41998547684338616
```

Keeping in mind that these values represent abstract additional costs applied to each trade route, we can interpret larger values of t_{ij} as additional geopolitical barriers of trade. For instance, one of the largest values returned is line 15 from Russia to Spain. In 2022 there were, and still are, significant barriers of trade between Russia and member states of the European Union. The t for Russia to the US is also one of the higher values. The only value that is unexpected enough to worth

5. Philip E. Gill et al., *SNOPT Version 7.5: Software for Large-Scale Nonlinear Programming*, v. version 7.5-1.2, Accessed: April 2024, 2015, https://ccom.ucsd.edu/~optimizers/solvers/snopt/.

commenting on is trade from Brazil to India, which is by far the highest value, at 4.04. For whatever reason, the model expected a higher of volume of oil to follow this trade rate, despite their far distance. Although unexpected, keeping this value high will make sure the model continues to keep trade between these countries realistically low.

While solving for these t_{ij} values, we can find a value for α at the same time. Running through different possible thresholds for diversification penalization from zero to one, the solver is run as before, solving for inferred values of t_{ij} with the goal of minimizing the MSE between our estimate x_{ij} and the real x^*_{ij}. Fortunately, there was only one clear local and global minimum, so for all future iterations α will be kept at 0.25.

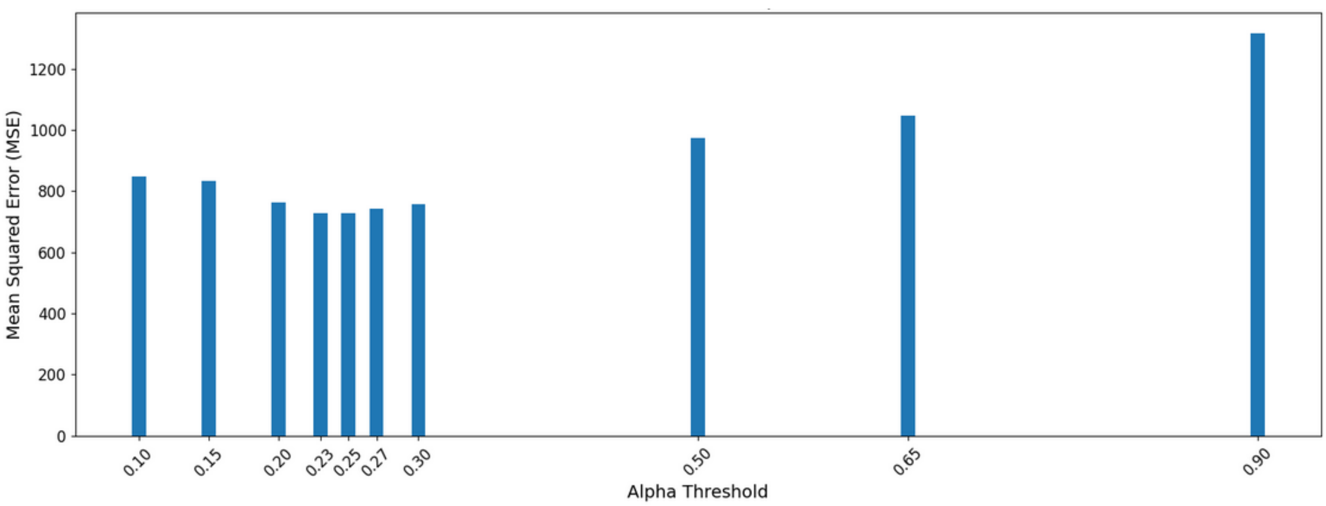

Figure 2: MSE calculated for values of α, with a minimum at $\alpha = 0.25$

Because there is still a non-negligible amount of error even with optimized parameters, it might be useful to examine the individual trade routes to look for potential sources of error.

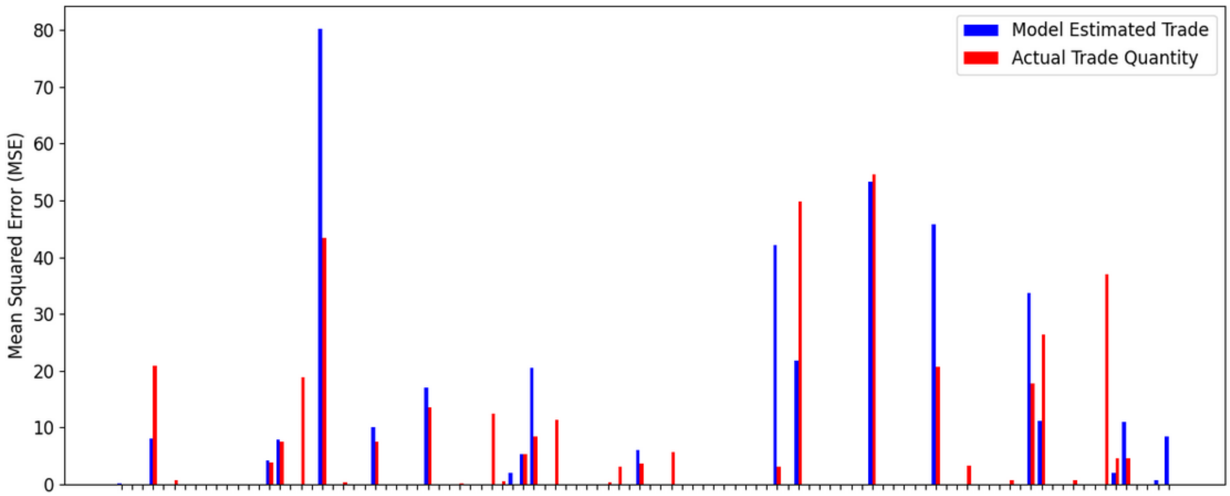

Figure 3: MSE of each x_{ij} at optimized t and α values, compared with real-world values x_{ij}

The above figure shows that the model is generally able to pick up on import trade routes, although there are notable exceptions. The following are all the trade routes with a an absolute error of more than one million tons:

```
('AE', 'TH'): -12.715348281551613,
('US', 'IN'): -18.907702279,
('SA', 'IN'): 36.67337322280027,
('SA', 'TH'): 2.4611674960817798,
('IQ', 'US'): 3.430528892365979,
('IQ', 'KR'): -12.452976,
('IQ', 'BR'): 2.088830569278896,
('BR', 'US'): 12.197830464,
('AE', 'KR'): -11.345278,
('BR', 'KR'): -3.0753543480000003,
('US', 'TH'): 2.3451683098558602,
('BR', 'ES'): -5.775038438,
('RU', 'KR'): 38.906036095,
('SA', 'KR'): -27.940170941255303,
('IQ', 'IN'): -1.361597570799404,
('AE', 'IN'): 25.01638362199918,
('BR', 'IN'): -3.2795009389999996,
('US', 'KR'): 15.91055320225531 5,
('SA', 'US'): -15.316856107365945,
('RU', 'IN'): -37.020204,
('SA', 'BR'): -2.4120137120008045,
('SA', 'ES'): 6.485818364883112,
('IQ', 'TH'): 8.371362163613972}
```

We can also plot these volumes in NetworkX for a more intuitive visual approach at our model validation, with each node representing a different country.

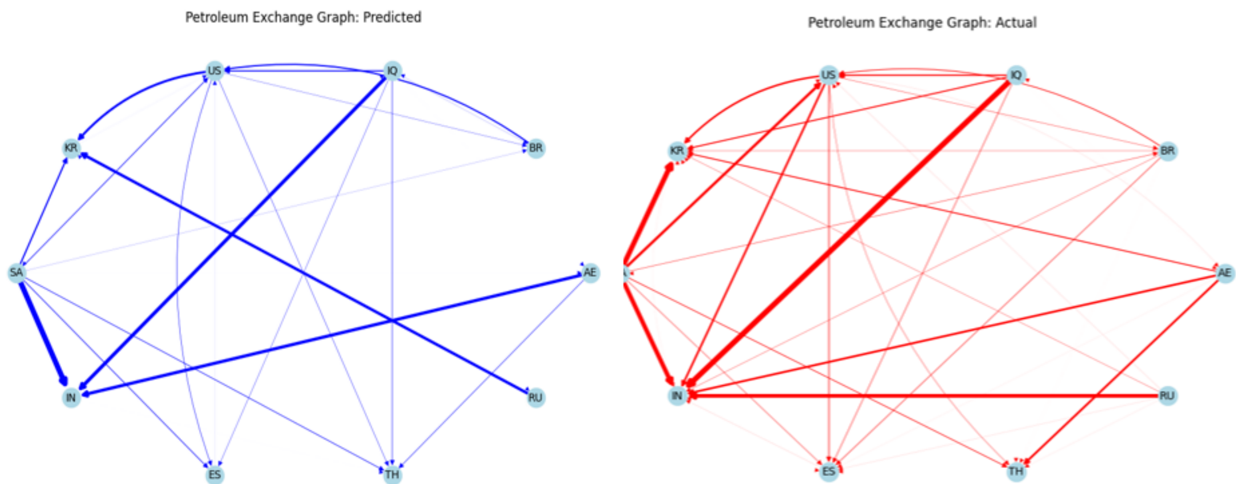

Figure 4: NetworkX Graphs Displaying Modelled Crude Oil Trade Volumes (Blue, Left) versus Actual (Red, Right)

Probably the most glaring of the errors is the models estimated 38 million tons of crude oil to be imported from Russia to Korea, almost none of which was present in the real data from CEPII. As these countries are some of the larger economies included in the model, it may make sense that their absolute errors are also larger. However, there are other explanations. Because my model only considers international maritime distances, there is potential that are costs for transporting crude oil within a country within a country that are not taken into account. In the case of Russia, it assumes that having crude oil available to export from its Black Sea ports costs the same as from Vladivostok. This is unlikely true, given that the majority of Russia's petroleum production occurs in western Siberia and the Volga region.[6] As a result of this not being included in the model, predicted Russian crude exports to Korea are likely inflated.

Although these possible sources of error are outside the capacity of my model to solve, it's important to acknowledge them and keep them in consideration when solving the next section. That said, we can now use our validated parameters to solve for the distances after the construction of the Kra canal.

6. "Russia's energy overview, 2022," U.S. Energy Information Administration, Accessed: May 19, 2024. Last Updated: April 29, 2024; Next Update: April 2025, April 29, 2024, accessed May 19, 2024, https://www.eia.gov/international/content/analysis/countries_long/russia.

4 Results

Taking the values of parameters t_{ij} and α solved in section 3, we can now update our costs c_{ij} to reflect the new distances following the construction of the Kra Canal. When we find the optimized trade volumes, it appears that they haven't changed much in comparison with the original values.

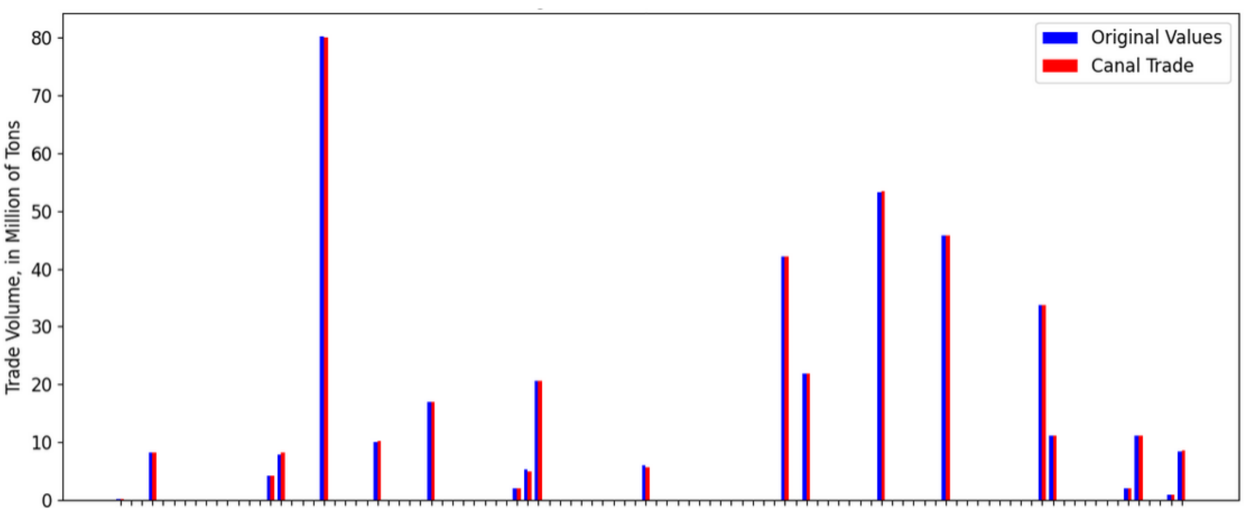

Figure 5: Predicted Trade Routes with Original Distances (Blue, Left), and Distances with the Kra Canal (Red, Right)

The following output displays all trade routes that experienced some change in volume.

```
('US', 'TH'), Change: -0.37370653671933773
('US', 'ES'), Change: 0.305535063716988
('IQ', 'ES'), Change: -0.28287351507797354
('SA', 'TH'), Change: 0.201481583395001
('IQ', 'TH'), Change: 0.17212488707983375
('IQ', 'IN'), Change: 0.16649646864590295
('SA', 'IN'), Change: -0.1663963879907584
('IQ', 'BR'), Change: -0.07760669531246123
('US', 'BR'), Change: 0.07760669531178532
('SA', 'ES'), Change: -0.02266154863901626
('SA', 'US'), Change: -0.021932088451167786
('IQ', 'US'), Change: 0.02193208845112693
('SA', 'KR'), Change: 0.009435313549843727
('US', 'KR'), Change: -0.009435313549779778
('AE', 'IN'), Change: -0.00010008065518007925
('AE', 'TH'), Change: 0.00010006624447278512
```

There is an intuitive explanation for most of the changes in optimal trade route assignment. First off, shipping costs from the Arab gulf to Thailand are now, so now Thai imports from Iraq and Saudi Arabia are both greatly increased. As a result, American exports to Thailand experience the largest reduction, and American exports to Spain the largest increase. Because of the limit size of the current model, most of the changes are that of a route that is directly shortened by the canal, or can clearly be seen as the effect of one that is. However, with more and more countries included in the model, these changes would likely include many butterfly effects that are hard to directly see the reason behind.

While the specific trade routes are important, we're also interested in seeing the macroeconomic effect on individual countries caused by the canal. Below is the output is the total percentage change of crude oil import costs for each country. Note that Russia, Iraq, and Saudi Arabia are not included on the table because they were not recorded as importing petroleum from any of the other selected countries in the BACI database.

```
UAE: Difference = 5.1253934208442
Brazil: Difference = 0.8170220996921617
South Korea: Difference = -2.8411589543718616
India: Difference = 0.05492769959185901
Spain: Difference = 1.7041333273616472
Thailand: Difference = -9.810143900525352
USA: Difference = -0.0057235883504034085
```

4.1 Sensitivity Analysis

Although it's generally uncontested that a Kra canal would reduce distances by about 1200 km, it's less certain how this reduction in distance would reduce costs. In section 2, I described how unit costs for each trade route were calculated by applying a fixed rate to the distance of each route in the distance matrix. This means that for the transit cost of any route passing through the Malacca strait c, the new transit cost would simply be $(c - 1200k)$, where k is any specified rate cost per kilometer.

Realistically, the updated costs of many of these trade routes would be more complicated than this, being affected by things like canal fees and varrying cost-per-distance relationships. For this reason, it's useful to conduct a sensitivity analysis involving the cost reductions of these paths. Instead of reducing the cost $(c-1200k)$, we can replace 1200 with any distance, effectively being able to see the macroeconomic effects as a function of how much this canal reduces costs.

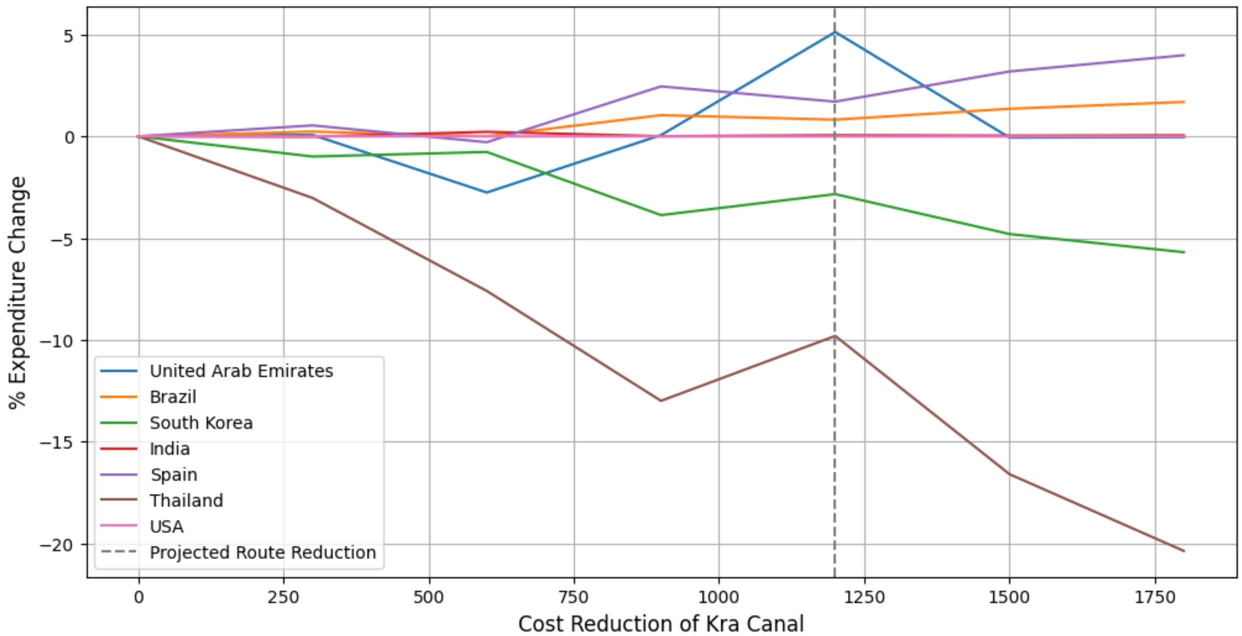

Figure 6: % Changes in Petroleum Expenditures per Country vs Fixed Canal Cost Reduction

In the above figure, the dotted vertical line shows the percent change of each country's petroleum import expenses at the expected distance reduction of the canal and its associated costs. To the left and the right, the figure explores possibilities of different costs. To clarify its interpretation, this isn't so much expressing uncertainty in the length of the canal, but rather how much it will reduce affected routes.

As the savings of the canal increase, the expenditures of Thailand quickly depart from the rest, reaching double digit percentage reductions as the canal savings approach the model's savings at 1200. Korea also sees expenditure reductions, albeit at a slower rate, as even though many of its routes may pass through the canal, they still have a far way to travel to reach Korea. Other countries such as USA and India appear mostly unaffected throughout the plot, while countries like Brazil and Spain seem mostly unaffected at first. However around 600km in savings (around half of the model's prediction), Spain and Brazil begin to see gradually increasing single digit increases in their crude oil import costs. Possibly most striking about the graph is local maximum that occurs at the expected canal price reduction. The spike for UAE can be somewhat dismissed by the fact that it is more of an petroleum exporter than importer, so a small absolute increase in price results in a significant percentage shift. On the other hand, the spikes in the primary beneficiaries of Thailand and Korea is much more surprising.

5 Discussion and Conclusion

Because of the limited amount of countries we were able to include in the model, the results have only shown a small slice of the large-scale impacts that such a canal would cause in global supply chains. Even though a more powerful solver would offer a more holistic analysis, the results as already computed show a clear logical intuition.

Besides simply adding more countries to the model, the integration of a stronger solver would also allow for more objective functions. With this, we could explore the minimization of costs from each individual country's perspective, which would be a more realistic simulation of macroeconomic behavior than simply minimizing the global cost of crude transportation. This point also raises the question regarding what level of international utilitarianism we are looking to resolve in an optimization such as this. In an increasingly cooperative world, trade route reductions that reduce costs and emissions should certainly be welcomed, but involved parties must also be aware of the potential negative effects this could have on other economies. Just one example is the negative repercussions that such a canal could have on the economy on Singapore, a strong economy whose economy benefits substantially by being a port city-state at the end of the strait of Malacca.

There is still much research needed before a canal like this will see fruition, but from these basic simulations, it shows strong potential to reduce costs and emissions of an important economic sector, and further cooperation of the international community could be key in ensuring that individual national benefits can transfer over as global benefits.

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