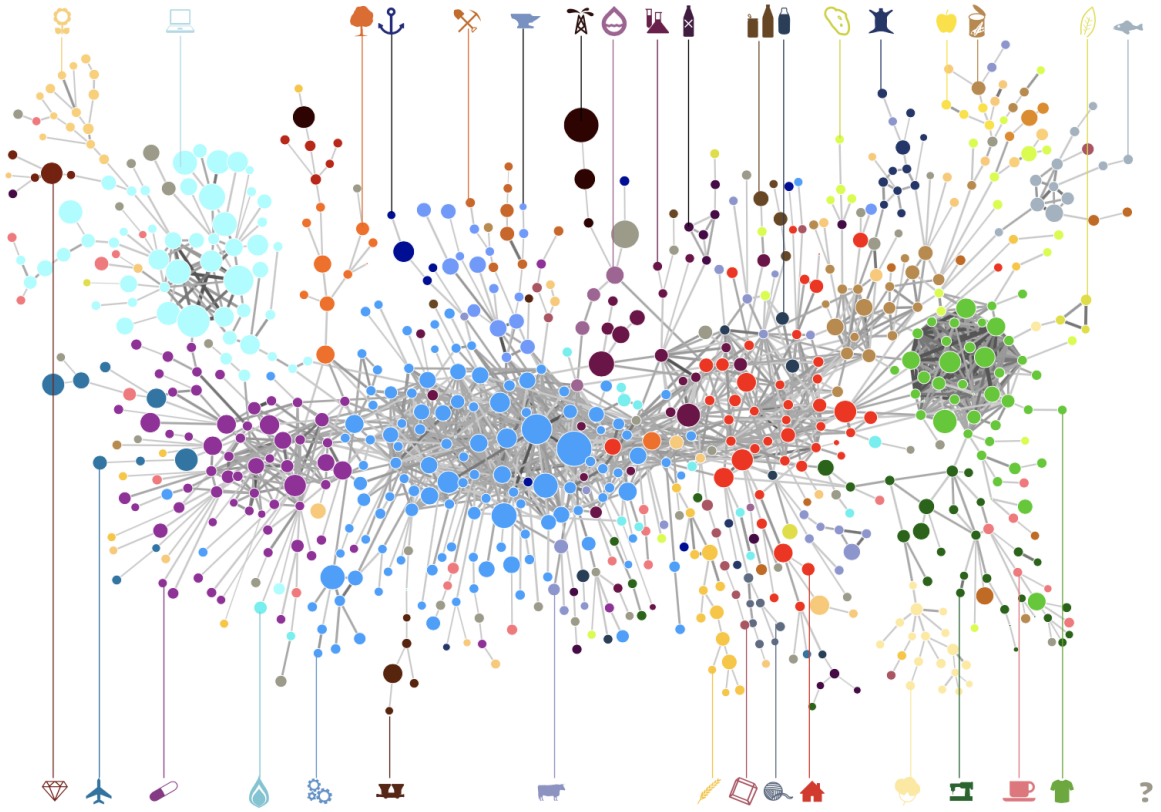

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Optimal Industry Development Strategy Using Economic and Product Complexity

Singapore

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The Economic Complexity Lab - Columbia University

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Optimal Industry Development Strategy for Singapore

0. Executive Summary

In this report, we aim to uncover the economic path Singapore went through during the period from 2013 to 2021. Specifically, we dive into the topic through a macroeconomic overview of Singapore from the perspective of Gross Domestic Product (GDP) and Economic Complexity Index (ECI), which reflect countries' production capability and production structure, respectively. We find that during the period of our interest, Singapore demonstrated a low level of economic growth with an average annual GDP growth rate of 3.6% between 2013 and 2018 and 2.31% between 2019 and 2021, with a decreased economic complexity compared to other major developed and emerging economies.

The negative progress during the period, we believe, can be partially explained through the analysis of the economic and product complexity structure of Singapore on the industry group level, as well as the declining macro and microeconomic strategies. The product classification system we adopt allows us to measure the realized industry development for various industry groups and to observe that Singapore regressed in developing most of its industries during the period while its developed and emerging counterparts and economies around the globe also adopted complex and progressive paths with variable degrees of success.

Based on our analysis of the opportunity gain and sensitivity analysis of major industry groups, Singapore could further its gains by prioritizing Chemicals, Machinery and Construction in 2018. Three years later, in 2021, its focus should shift to the Energy Drilling and Mining and Precious Stones industries, which are also one of the more developed industries at the time. We further note that Singapore has a slightly mismatched development strategy that indicates a moderate level (compared to other developed and emerging countries) of structural optimality on the complexity level, having an adjusted R-square of around -5.1% in 2018 and a much higher score of 39.1% in 2021, demonstrating shift and improvement in development. Since a significant positive correlation exists between five-year GDP growth between 2013 and 2018 and the structural optimality index of an economy as we define and calculate, Singapore indeed has a suboptimal growth experience as compared with fast-growing economies both on a regional scale and on a global scale and has the potential to further its economic gains through industrial structure optimization as suggested in the paper.

The three years following showed a significant improvement in Singapore's economic growth, boosting its position on the global scale. Its GDP recovered to above the pre-pandemic levels, and it saw a significant boost in the ECI, particularly compared to its peer countries. Its current strategy still has the viable potential upside to increase its performance and optimize its structure further.

1. Report Overview

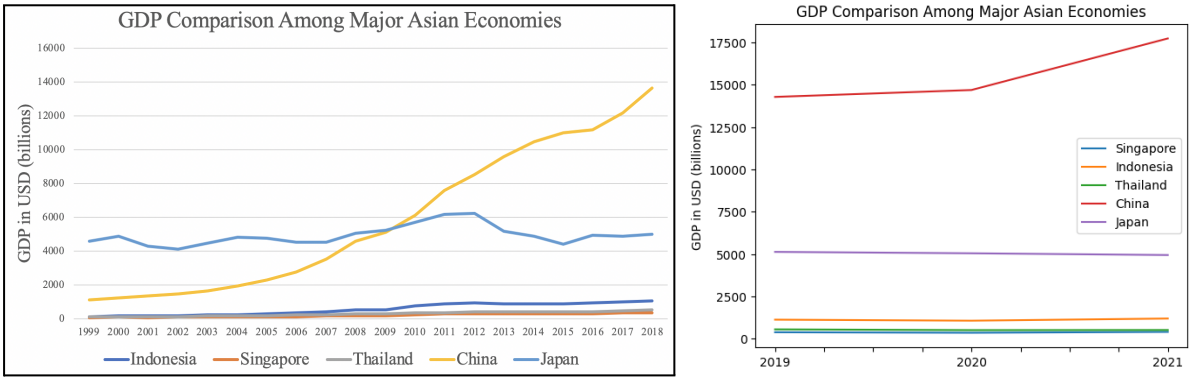
In this report, we aim to uncover the economic path Singapore went through during the period from 2019 to 2021, before and after the COVID pandemic, compared to its performance from 2013 to 2018. Specifically, we dive into the topic through a macroeconomic overview of Singapore from the perspective of Gross Domestic Product (GDP) and Economic Complexity Index (ECI), which reflect countries' production capability and production structure, respectively. We then analyze the industrial framework and changes of Singapore during the period based on quantitative measures such as the Product Complexity Index (PCI) and Product Family Complexity Index (PfCI), followed by a detailed analysis of how such changes have matched with development strategies as quantitatively measured by opportunity gains on an industry-level. We conclude our report with macro-level results and predictions of Singapore, as deduced from regression models we have established on a global scale, which take into account countries' stances in their product space.

2. Macroeconomic Results

2.1 GDP Ranking and Changes

Figure 1a illustrates the time-series GDP results for Singapore and four other major Asian economies (Indonesia, Thailand, China and Japan) from 2013 to 2018. Singapore ranks among its peers as a small but growing economy in terms of both GDP and GDP growth. During the period from 2013 to 2018, Singapore achieved an average annual growth of 3.6% in GDP. This number is slightly higher than the annual growth rate of the other four leading Asian economies, which have a geometric average growth rate of 3.0% and an arithmetic average growth rate of 3.2%. Compared with more developed economies on a global scale, the annual growth rate of 3.6% is comparable to countries such as the USA which has an average annual GDP increase of around 4% during the period.

Figure 1b shows the GDP levels for Singapore and other major Asian economies (Indonesia, Thailand, China, and Japan) from 2019 to 2021. Similar to the other countries, Singapore displayed a drop in GDP from 2019 to 2020 because of the pandemic, with all GDPs rebounding in 2021. Over these three years, Singapore's average annual GDP growth rate (2.31%) is in the lead, as it is greater than Indonesia's rate (2.21%), Thailand's rate (-2.3%), and Japan's rate (-1.22%), but less than China's rate (7.87%).



Figures 1a and 1b. GDP Comparison Among Peer Countries (left: 2013-2018; right: 2019-2021)

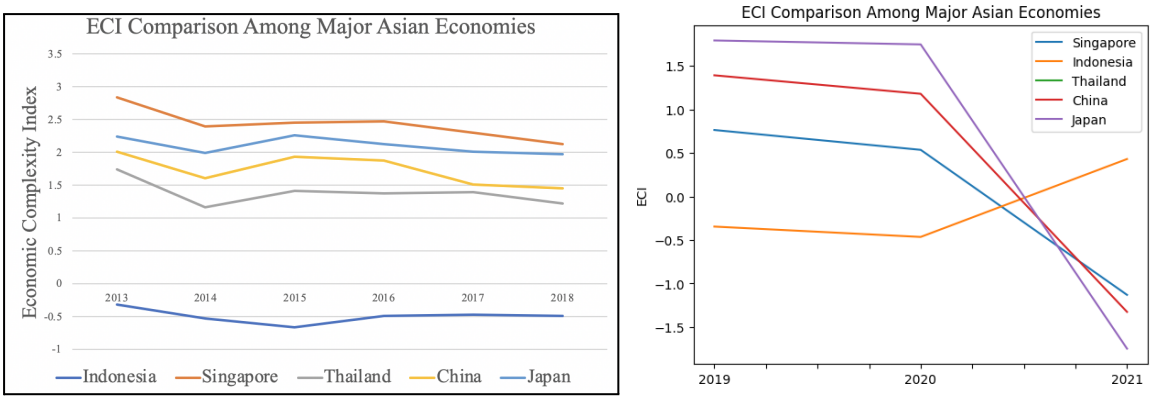
2.2 ECI Ranking and Changes

The Economic Complexity Index (ECI), as defined by Ricardo Hausmann and Cesar Hidalgo in 2009 to explain the knowledge accumulated in a country's population, is illustrated in Figures 2a and 2b.

As shown, Singapore exhibits a stably high production capability from 2013 to 2018, as measured by ECI. This is in direct contrast to the other Asian economies such as Indonesia, which demonstrates a huge disadvantage in both ECI growth rate and GDP growth rate.

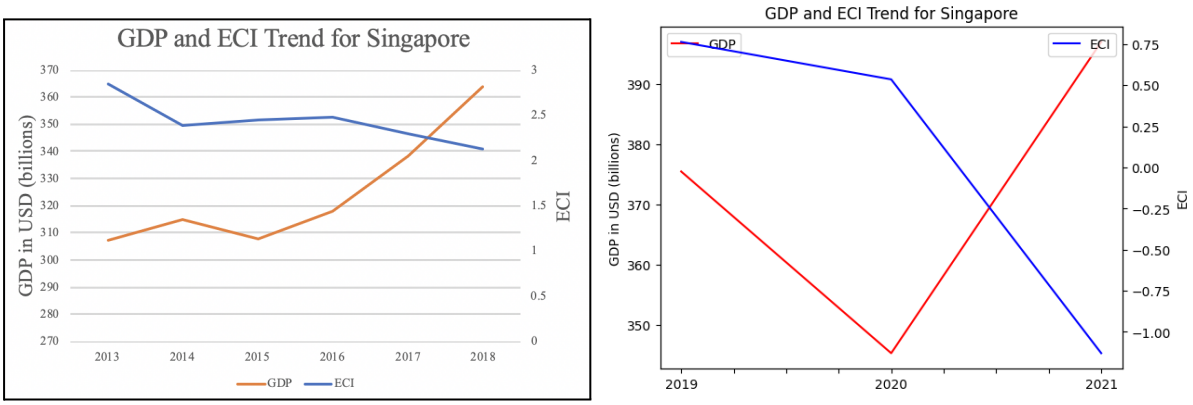
The comparable countries maintain a small change in ECI level between 2019 and 2020, with a sharp change between 2020 and 2021. Singapore and peer countries such as Japan and

China saw significant decline in ECI values. Singapore has seen a -247.91% increase in its ECI, which is less than Indonesia's (224.61%), China's (-195.21%), and Japan's (-197.52%).



Figures 2a and 2b. ECI Comparison Among Peer Countries (left: 2013-2018; right: 2019-2021)

Figures 3a and 3b offer a further comparison of GDP Growth and ECI over the time span from 2013 to 2021 for Singapore. Similar to the GDP drop and further increase from 2013 to 2018, the GDP growth during the period from 2019 to 2021 is accompanied by a similarly volatile increase in ECI. The results show that the economic growth experienced by Singapore during the period from 2013 to 2018 is only partially consistent with the predictions by ECI and that Singapore made weak progress towards effectively developing a competitive product space that helps to accumulate complicated knowledge and technology. For the period 2019 to 2021, the ECI did not follow GDP trends. In order to provide a more concrete answer to why this has happened, we will dive into an analysis of Singapore's production structure and its product space designs in the next few sections.



Figures 3a and 3b. GDP Growth and ECI for Singapore (left: 2013-2018; right: 2019-2021)

3. Production Analysis

3.1 Product Categorization

Our main data source in this research is the UN Comtrade Website (https://comtrade.un.org), which provides us with valuable information on countries' export values on an annual basis, including highly specific export data for more than 5000 categories of products. In order to have a holistic vision of the product space of a country, however, a level of categorization is required. Products in our data source are labeled from 010000-999999, with the first two digits representing a general category to which the product belongs. Based on the 99 categories extracted from the label, we further group the products into the 18 most widely-accepted industries, as summarized in Table 1.

Note that the High-complexity Products industry group is not a distinct industry but rather an aggregated industry that encompasses the most complicated products from the most technologically-advanced industries (as measured by PCI). This industry serves as an indicator for us to quantitatively evaluate how well a country has performed in developing cutting-edge technologies and closing its technological gap with advanced economies, which has become a topic of wide concern today. Indeed, when we rank the 18 categories based on PfCI (an equivalent concept of PCI as calculated based on the 18 categorized product groups), the High-complexity Products industry has the highest PfCI among all industry groups.

Category	Description
Animals and By-products	All kinds of meat, livestock and related by-products
Vegetables, Fruits and Plants	All kinds of plants, edible vegetables and fruits
Food and Preparations	Edible preparations, raw cooking materials and appliances
Clothing and Accessories	All kinds of fabrics, filament, clothing and accessories
Textiles	All kinds of textile articles and related products
Wood Products	Book, paper and other elementary products related to wood
Metals	Mining of all sorts of raw Metals
Refined and Processed Stones	Refined or processed stone products such as pearl and ceramics
Energy Drilling and Mining	Mining industry for energy, minerals, stone materials, etc.
Daily Instruments	Basic daily instruments such as sport requisites, timing and measuring tools
Raw Manufacturing	Basic products made from plastic, rubber, leather, etc.
Chemical Manufacturing	Advanced chemical products and pharmaceutical products
Chemicals	Raw chemical materials and by-products
Machinery and Construction	Machinery and mechanical appliances, including electrical equipment
Transportation	Vehicles and locomotives including aircraft, ship, railway, etc.
Weapons	Explosives, arms and ammunition
Services and Utilities	Financial, business, legal, communication, travel Services and Utilities, etc.
High-complexity Products	Agglomeration of advanced products with highest PCIs

Table 1. Categorization of Products

We further observe a positive correlation between the GDP and the export of High-complexity Products. A higher adjusted R-square exists between GDP and High-complexity Products exports, indicating that more successful economics, as measured by GDP, tend to be those that are capable of producing and exporting High-complexity Products as we define them. Tables 2a and 2b show the OLS results in a universe of 107 and 21 typical countries respectively.

	High-complexity Products	Food and Preparations	Animals and By-products
Adj. R-squared	0.075	0.006	0.002
F-statistic	9.556	1.638	1.175
No. Observations	107	107	107

Table 2a. OLS Regression Results of GDP against Percentage Volume of Exports

	High-complexity Products	Food and Preparations	Animals and By-products
Adj. R-squared	0.149	0.003	-0.012
F-statistic	4.510	1.059	0.7542
No. Observations	21	21	21

Table 2b. OLS Regression Results of GDP against Volume of Percentage Exports

3.2 Realized Industry Development

Based on the aforementioned product categorization, we aim to capture Singapore's realized industry production strategy between 2013 and 2021 on a complexity level. In Hausmann and Hidalgo (2009), distance is defined to be a measure of how far a country is from a certain product, not in its product space. We extend this concept to all product groups and quantify how technically equipped a country is to develop the corresponding product groups. In other words, the shorter the distance between a country and a product group, the more capable a country is of developing products within that group. Defining this net distance change as the Realized Industry Development (RID), our export data allow us to calculate and compare the RID of Singapore and the 18 product groups in 2021 and 2018 through the difference, where a positive RID indicates a shortening of the distance (i.e., advancement of the industry), and a negative RID indicates the reverse. It is notable that the number of industries with positive RID has decreased from two to one from 2018 to 2021.

Category	RID (2021)	RID (2018)
Daily Instruments	-0.037	-0.064
Chemicals	-0.045	-0.028
Weapons	0.006	-0.026
Wood Products	-0.041	-0.020
Transportation	-0.000	-0.107
Machinery and Construction	-0.009	0.018
Metals	-0.063	-0.032
Raw Manufacturing	-0.015	-0.022
Services and Utilities	-0.045	-0.063
Clothing and Accessories	-0.058	-0.008
Chemical Manufacturing	-0.013	-0.016
Food and Preparations	-0.053	-0.015
Textile	-0.015	-0.022
High-complexity Products	-0.010	-0.090
Vegetables, Fruits and Plants	-0.037	-0.020
Animals and By-products	-0.046	-0.017
Energy Drilling and Mining	0.000	0.000
Precious Stones		

Table 3. Realized Industry Development (RID) of Singapore

3.3 Regional and Global Comparison

Tables 4a-4b below summarize how the production strategy adopted by Singapore compares with selected leading economies in the world across different years, as measured in RID. Leading economies such as France, the United States, and Germany gave a considerable level of attention to more advanced product groups such as high-complexity products and food and preparations in 2018 and precious stones, energy drilling and mining, and services and utilities in 2021.

Ranking	France	The United States	Germany
1	High-complexity Products	Services and Utilities	High-complexity Products
2	Chemical Manufacturing	Weapons	Transportation
3	Daily Instruments	Raw Manufacturing	Wood Products
4	Animals and By-Products	Precious Stones	Metals
5	Food and Preparations	Animals and By-products	Food and Preparations

Table 4a. RID Comparison across Leading Economies (2018)

Ranking	France	The United States	Germany
1	Services and Utilities	Precious Stones	Daily Instruments
2	Precious Stones	High-complexity Products	Transportation
3	High-complexity Products	Services and Utilities	Chemicals
4	Energy Drilling and Mining	Energy Drilling and Mining	Chemical Manufacturing
5	Machinery and Construction	Wood Products	Clothing and Accessories

Table 4b. RID Comparison across Leading Economies (2021)

Tables 4c-4d further examine Singapore's development strategy against those of emerging economies on a global scale. Reasonably, emerging economies such as China, South Korea, and Singapore have devoted the majority of their efforts to intermediate industry groups, showing moderate shifts in strategies over the course of three years.

Ranking	China	South Korea	Singapore
1	High-complexity Products	Transportation	Transportation
2	Transportation	Textile	High-complexity Products
3	Machinery and Construction	High-complexity Products	Precious Stones
4	Energy Drilling and Mining	Chemical Manufacturing	Daily Instruments
5	Daily Instruments	Machinery and Construction	Services and Utilities

Table 4c. RID Comparison across Emerging Economies (2018)

Ranking	China	South Korea	Singapore
1	Chemicals	Chemicals	Weapons
2	Daily Instruments	Daily Instruments	Energy Drilling and Mining

3	Transportation	Transportation	Transportation
4	Raw Manufacturing	Textile	Machinery and Construction
5	Weapons	Raw Manufacturing	High-complexity Products

Table 4d. RID Comparison across Emerging Economies (2021)

4. Product Space Design

4.1 Suggested Development Vector

As outlined above, distance gives us an idea of how far each new product is from a country's current mix of exports. As defined in Hausmann and Hidalgo (2009), distance is "the weighted proportion of products connected to goods p that country c is not exporting, i.e., MCP = 0." Based on this definition, the distance between a country and any product that the country is currently exporting (i.e., the country is a significant exporter of the product as compared to the global average) is zero. Similarly, opportunity gain quantifies the contribution of a new product in terms of opening up the doors to more and more complex products. Intuitively, a product that a country is currently exporting (i.e., MCP = 1) has an opportunity gain of zero. An unreasonable investment in a certain product p would lead to a relative decrement in the export of more profitable products and therefore lead to a negative opportunity gain of product p. The opportunity gain is not the only estimator of a country's level of economic development. However, among countries with comparable economic strength, those having higher ECI, or in other words, more reasonable economic structures are often in better shape.

Rank	Singapore	China	Germany
1	Chemicals	Raw Manufacturing	Chemical Manufacturing
2	Transportation	Clothing and Accessories	Wood Products
3	High-complexity Products	Textile	Metals
4	Services and Utilities	Machinery and Construction	Machinery and Construction
5	Machinery and Construction	Transportation	Transportation
6	Daily Instruments	Weapons	Weapons
7	Weapons	Daily Instruments	High-complexity Products
8	Textile	High-complexity Products	Services and Utilities
9	Chemical Manufacturing	Precious Stones	Energy Drilling and Mining
10	Raw Manufacturing	Services and Utilities	Precious Stones
11	Clothing and Accessories	Chemicals	Textile
12	Metals	Energy Drilling and Mining	Clothing and Accessories
13	Wood Products	Chemical Manufacturing	Chemicals
14	Precious Stones	Wood Products	Animals and By-products
15	Animals and By-products	Animals and By-products	Vegetables, Fruits, and Plants
16	Food and Preparations	Vegetables, Fruits, and Plants	Food and Preparations
17	Energy Drilling and Mining	Metals	Daily Instruments
18	Vegetables, Fruits, and Plants	Food and Preparations	Raw Manufacturing
ECI	**2.751108815**	**1.96086598**	**1.937171566**

Table 5a. Opportunity Gain Ranking on a Comparable Scale (2013)

Rank	Singapore	China	Germany
1	Energy Drilling and Mining	Chemicals	Chemical Manufacturing
2	Chemicals	Raw Manufacturing	Machinery and Construction
3	Machinery and Construction	Clothing and Accessories	Transportation
4	Transportation	Textile	Daily Instruments
5	High-complexity Products	Machinery and Construction	High-complexity Products
6	Services and Utilities	Transportation	Services and Utilities

7	Weapons	Weapons	Chemicals
8	Textile	Daily Instruments	Textile
9	Precious Stones	High-complexity Products	Weapons
10	Chemical Manufacturing	Precious Stones	Clothing and Accessories
11	Clothing and Accessories	Services and Utilities	Precious Stones
12	Daily Instruments	Energy Drilling and Mining	Raw Manufacturing
13	Animals and By-products	Wood Products	Wood Products
14	Metals	Animals and By-products	Energy Drilling and Mining
15	Raw Manufacturing	Metals	Animals and By-products
16	Wood Products	Chemical Manufacturing	Metals
17	Vegetables, Fruits, and Plants	Vegetables, Fruits, and Plants	Food and Preparations
18	Food and Preparations	Food and Preparations	Vegetables, Fruits, and Plants
ECI	**2.112887919**	**1.700687855**	**2.959929484**

Table 5b. Opportunity Gain Ranking on a Comparable Scale (2018)

Rank	Singapore	China	Germany
1	Chemicals	Chemical Manufacturing	Chemical Manufacturing
2	Machinery and Construction	Clothing and Accessories	Raw Manufacturing
3	Transportation	Transportation	Wood Products
4	Precious Stones	Weapons	Machinery and Construction
5	Services and Utilities	Daily Instruments	Transportation
6	Metals	Precious Stones	Weapons
7	Chemical Manufacturing	Services and Utilities	Daily Instruments
8	Clothing and Accessories	Energy Drilling and Mining	High-complexity Products
9	High-complexity Products	High-complexity Products	Energy Drilling and Mining
10	Raw Manufacturing	Textile	Precious Stones
11	Wood Products	Metals	Clothing and Accessories
12	Textile	Wood Products	Textile
13	Animals and By-products	Chemicals	Food and Preparations
14	Vegetables, Fruits and Plants	Animals and By-products	Vegetables, Fruits and Plants
15	Daily Instruments	Vegetables, Fruits and Plants	Animals and By-products
16	Food and Preparations	Raw Manufacturing	Services and Utilities
17	Energy Drilling and Mining	Machinery and Construction	Chemicals
18	Weapons	Food and Preparations	Metals
ECI	**-1.129920784**	**-1.861282363**	**-1.325400334**

Table 5c. Opportunity Gain Ranking on a Comparable Scale (2021)

We define the ranking of opportunity gain for a country c, as the Suggested Development Vector (SDV) of c. Tables 5a-5c summarize how the SDV of Singapore compares with a selected group of comparable and leading economies in the world, with the industry groups ranked in decreasing order of significance. We focus on SDV results for 2018 because they give the most accurate snapshot of complexity for global comparison in the absence of the irregular effects of the COVID-19 pandemic observed in 2021.

Light blue indicates zero opportunity gains and white indicates negative opportunity gains. There were no industries that have positive opportunity gain. In other words, those countries are already in the most stable and efficient economic structure. Without the necessity of economic transition, those countries merely need to maintain a steady and balanced economic

development. In contrast, developing countries have nearly half of industries with positive opportunity gain. It can be concluded that Singapore shares the characteristics of developed countries, with a balanced economic structure that leans towards high-level industries.

Rank	The United States	South Korea	Japan	Indonesia
1	Animals and By-products	Chemicals	Chemicals	Animals and By-products
2	Vegetables, Fruits and Plants	Raw Manufacturing	Raw Manufacturing	Vegetables, Fruits and Plants
3	Food and Preparations	Textile	Metals	Food and Preparations
4	Energy Drilling and Mining	Metals	Transportation	Energy Drilling and Mining
5	Chemicals	Transportation	Weapons	Chemicals
6	Raw Manufacturing	Daily Instruments	Daily Instruments	Raw Manufacturing
7	Wood Products	Services and Utilities	High-complexity Products	Wood Products
8	Clothing and Accessories	Chemical Manufacturing	Services and Utilities	Clothing and Accessories
9	Textile	Energy Drilling and Mining	Energy Drilling and Mining	Textile
10	Metals	Clothing and Accessories	Clothing and Accessories	Metals
11	Machinery and Construction	Precious Stones	Food and Preparations	Machinery and Construction
12	Weapons	Wood Products	Precious Stones	Weapons
13	Precious Stones	Food and Preparations	Chemical Manufacturing	Precious Stones
14	Services and Utilities	High-complexity Products	Wood Products	Services and Utilities
15	Transportation	Animals and By-products	Vegetables, Fruits and Plants	Chemical Manufacturing
16	Chemical Manufacturing	Vegetables, Fruits and Plants	Animals and By-products	High-complexity Products
17	Daily Instruments	Machinery and Construction	Textile	Transportation
18	High-complexity Products	Weapons	Machinery and Construction	Daily Instruments
ECI	**0.6301643562**	**1.519092735**	**1.792342474**	**-0.345375137**

Table 6. SDV of Other Sample Countries (2019)

4.2 Budgeted Industry Development Strategy and Interpretation

The optimal budgeted industry development strategy aims to solve the most efficient allocations under the budgeted constraint of different situations of heuristic total export growth. In order to obtain such an allocation portfolio, we formulate an optimization problem as the following:

$$\max_{x \in \mathbf{R}^{|P|}} \quad \left(\frac{k(x) - < k(x) >}{stdev(k(x))}\right)_C$$

Subject to

$$\sum_{p \in P} x_p \leq B$$

$$x \succcurlyeq 0$$

where k(x) is the second largest eigenvector of $M_{CC'}$ after adding x to the original export vector, C is the country that we are interested in, P is the product space, B is the heuristic budget.

If we can solve this problem, then we can know what the largest ECI to which a country can improve. Accordingly, the optimal solution x * that we obtain here is exactly our optimal allocation. However, the biggest problem is that the objective function is not convex. Therefore, we cannot apply the classical tools for convex optimization to this problem. In order to solve this problem, our idea is to use a greedy algorithm. The way that we apply the greedy algorithm is that firstly we separate the total budget into k equal parts, and then for the first equal part we try to search for the product that can optimize our objective function by iterating through each $p \in P$. After we find the optimal product p for this equal part, we add the amount back to the export value of this product p and update the ECI for this country. If we observe that ECI does not change after iterating all the products, then we can add up one more equal part to invest. Until we find there is an ECI increment, we add the amount now to that product. The equal rest parts can be done in the same way.

By definition, a greedy algorithm is a kind of local search algorithm that is possible to run into a local minimum. Therefore, for local search algorithms, one typical way to keep it away from the local minimum is to enhance the vision of the algorithm by looking more steps forward. In our setting, whenever we obtain an increment of ECI, we mark down the required amount of export growth. Simultaneously, we continue searching for the next ECI increment point, compare the ratios of these two possibilities and pick the largest one. The ratio is defined as the following:

$$Ratio(p) = \frac{ECI_p - ECI_0}{||x_p - x_0||_1}$$

where ECI_p is just the ECI of the country after adding some amount of export increment to product p, which is exactly the amount that is able to make ECI change. Also, we can express it in the way of $||x_p - x_0||_1$.

In this way, we can obtain a further sighted greedy algorithm. Also, the number of parts that we would like to separate the budget into also matters. In order to solve this problem, we added a stabilizer on top of the enhanced greedy algorithm by running the algorithm for different numbers of parts and selecting the portfolio with the largest ECI increment and most complex economic structure.

Besides, it is quite common that there is a surplus in the budget. To deal with the surplus, we just add it to the product which needs the least amount of dollars to make $M_{cp} = 1$ (i.e., the smallest amount of required export increase).

Economic Panel

As stated above, the enhanced greedy algorithm is developed mainly for solving the optimal allocation strategy. In order to visualize this allocation, an economic panel is created, consisting of a pie chart, a line chart and a table. First, a pie chart is used to show the percentage of each product in the optimal portfolio. The number located in the center of the circle denotes the heuristic growth of total export, which is also our budget. Each category in the chart has a determined percentage of the allocated budget. The lines below the pie charts show how the ECI changes during the searching process of the greedy algorithm. Even though sometimes an increase of the export by 15% or 20% does not seem reasonable to developed countries, yet it can also give a sense of how a country should develop in the long term. Eventually, the graph in the end is just for numerical explanation for the pie charts.

Interpretation

For the purpose of a clear explanation of the line charts, we label all the products in Table 7. Please refer to this table when trying to understand the investment trajectories in the line charts.

Label	Product Names
1	Animal and By-products
2	Vegetables, Fruits and Plants
3	Food and Preparations
4	Energy Drilling and Mining
5	Chemicals
6	Chemical Manufacturing
7	Raw Manufacturing
8	Wood Products
9	Clothing and Accessories
10	Textile
11	Metals
12	Machinery and Construction
13	Transportation
14	Weapons
15	Daily Instruments
16	Precious Stones
17	High-complexity Products
18	Services and Utilities

Table 7. Products Labeling

Figures 4a-4c show an economic panel for Singapore in 2013, 2018, and 2021. We can see that for different percentages of heuristic total export growth, the ECIs of Singapore actually have different increments.

For 2013, we can see that for different percentages of heuristic total export growth, the ECI of Poland has relatively similar performance. From all the four line graphs, we see that

Singapore obtains some great increment in terms of ECI. However, increasing the budget for too large an amount would not produce a higher and higher ECI. Also the optimal ECI that we can achieve is the same for each case. This means that in longer terms, Singapore does not have a lot of room to improve. For the four export growth budget, the increment of ECI depends on chemicals, machinery and construction. A more detailed numerical representation of the portfolio is shown in Table 8a.

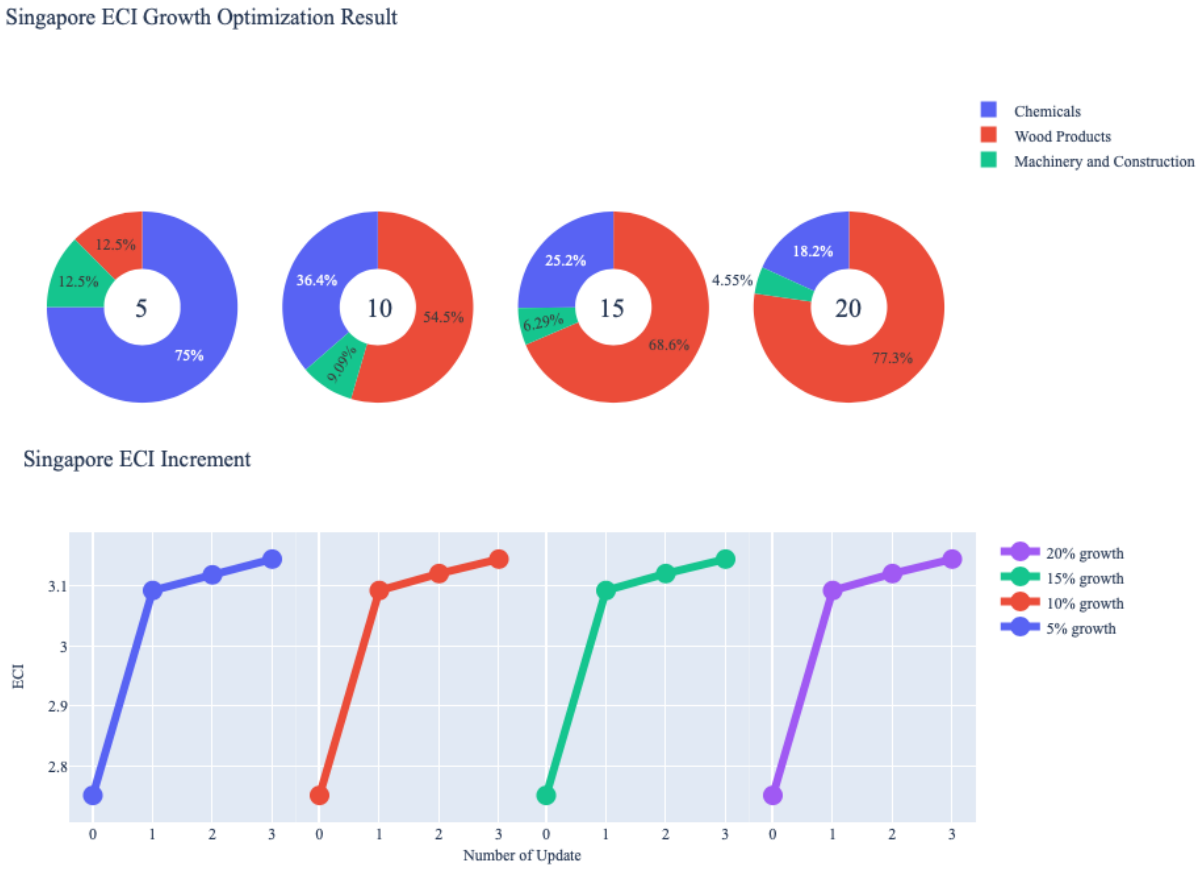


Figure 4a. Greedy-Based ECI Improvement Results of Singapore with Different Budgets (2013)

Singapore (2013)				
Original ECI			**2.751**	
Heuristic Export Growth	**5%**	**10%**	**15%**	**20%**
Heuristic Export Growth (US. $)	3.22E+10	6.44E+10	9.66E+10	1.29E+11
Machinery and Construction (US. $)	4.02E+09	5.85E+09	5.85E+10	5.85E+09
Wood Products (US. $)	4.02E+09	3.51E+10	6.38E+10	9.95E+10
Chemicals (US. $)	2.41E+10	2.34E+10	2.34E+10	2.34E+10
Increased ECI	**3.144**	**3.144**	**3.144**	**3.144**

Table 8a. Portfolio of Singapore (2013)

For further suggestions on Singapore's development in the future, we also offer the optimization result of Singapore based on export data in 2018. Below is the economic panel for Singapore in 2018. We can see that for different percentages of heuristic total export growth, the ECI growth pattern of Singapore is similar to the one in 2013. From all the four line graphs, it still reaches the same optimal ECI eventually. This means that Singapore does not have a lot of room to improve, especially for the case of 5% growth, where the increment

of ECI can barely be observed. However, our optimization method shows Singapore still can have gains by investing in machinery and construction, services industry and high complexity products. Therefore, for future strategy, Singapore should prioritize development of these three products in order to optimize the ECI.

A more detailed numerical representation of the portfolio is shown in Table 8b.

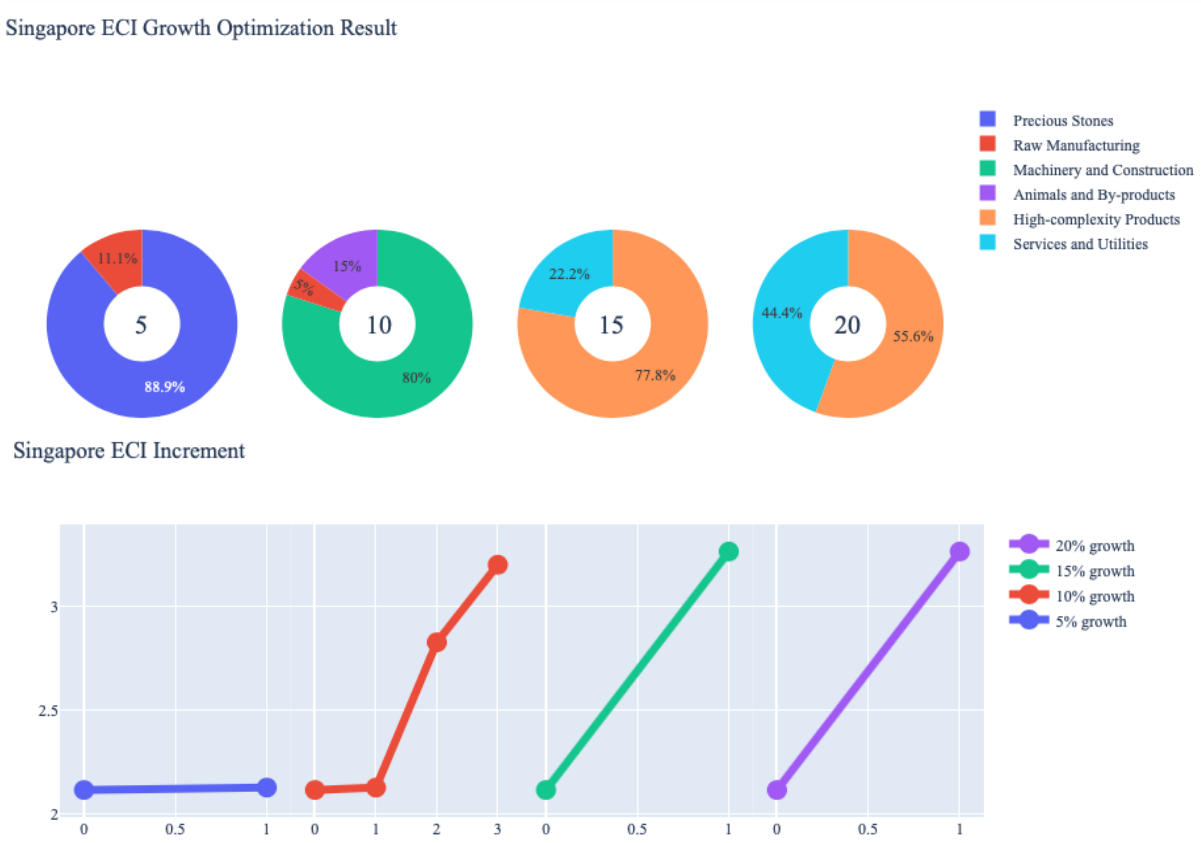


Figure 4b. Greedy-Based ECI Improvement Results of Singapore with Different Budgets (2018)

Singapore (2018)				
Original ECI			**2.11**	
Heuristic Export Growth	**5%**	**10%**	**15%**	**20%**
Heuristic Export Growth (US. $)	3.22E+10	6.44E+10	9.65E+00	1.29E+11
Animals and By-products (US. $)	0.00E+00	9.65E+09	0.00E+00	0.00E+00
Raw Manufacturing (US. $)	3.58E+09	3.22E+09	0.00E+00	0.00E+00
Machinery and Construction (US. $)	0.00E+00	5.15E+10	0.00E+00	0.00E+00
Precious Stones (US. $)	2.86E+10	0.00E+00	0.00E+00	0.00E+00
High-complexity Products (US. $)	0.00E+00	0.00E+00	7.51E+10	7.15E+10
Services and Utilities (US. $)	0.00E+00	0.00E+00	2.15E+10	5.72E+10
Increased ECI	**2.12**	**3.20**	**3.27**	**3.27**

Table 8b. Portfolio of Singapore (2018)

To compare with the performance in 2013 and 2018, we also re-examine suggested strategies for 2021. For 2021, a 5 percent increase in export would emphasize High-complexity Products, followed by Energy Drilling and Mining for 10 and 20 percent export growth and Precious Stones for 15 percent export growth. These strategies go in line with the suggested trajectories based on ECI. Our line graph in figure 4c shows the most growth potential in

investing in Precious Stones followed by Energy and Drilling. Increased investment in High-complexity Products will produce a positive output, but not as great compared to the other two categories. A more detailed numerical representation of the portfolio for Singapore is shown in Table 8c.

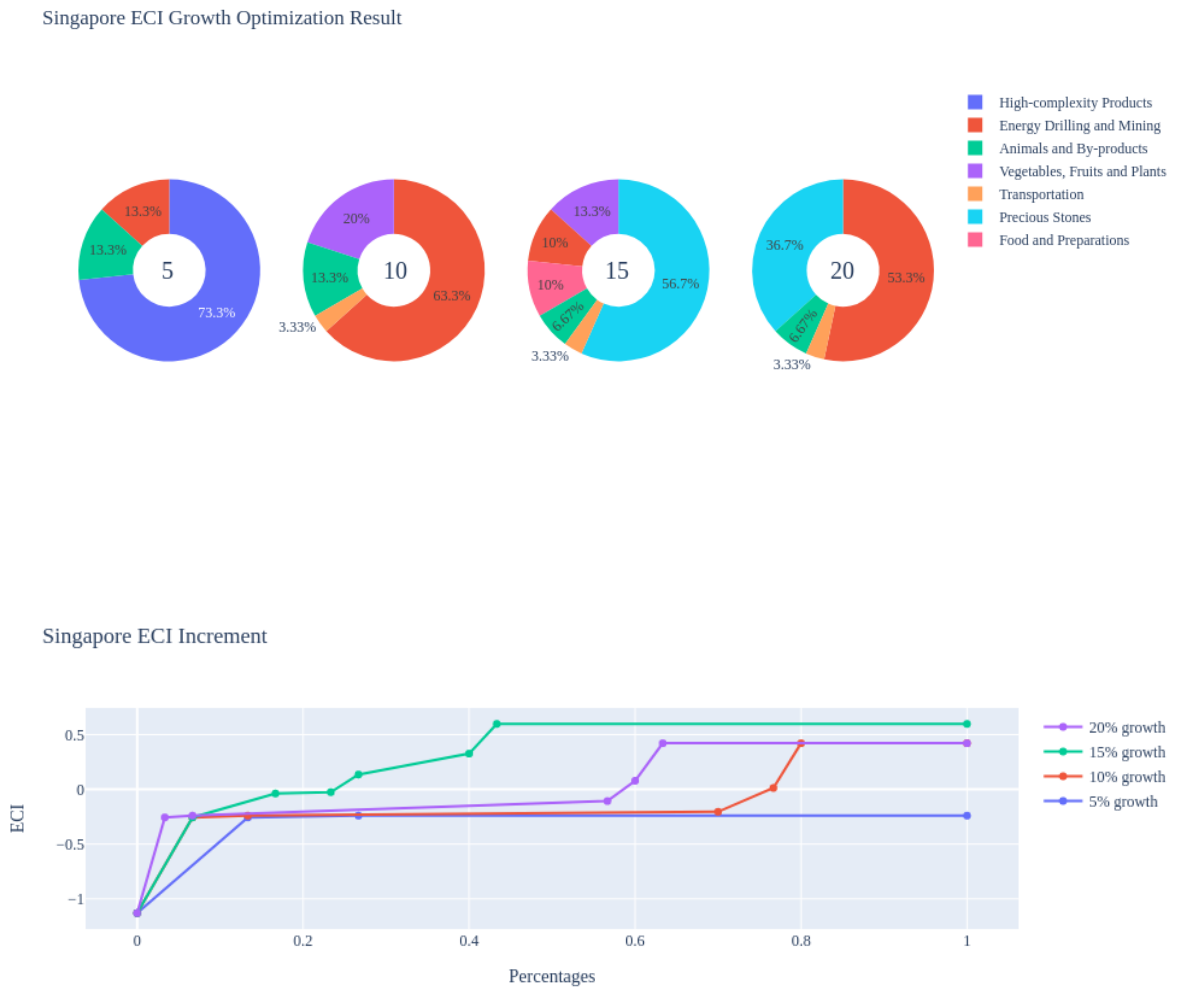


Figure 4c. Greedy-Based ECI Improvement Results of Singapore with Different Budgets (2021)

Singapore (2021)				
Original ECI		**-1.130**		
Heuristic Export Growth	**5%**	**10%**	**15%**	**20%**
Energy Drilling and Mining	3.44E+09	3.44E+09	5.17E+09	5.86E+10
Animals and By-products	6.90E+09	6.90E+09	1.81E+10	6.20E+10
High-complexity Products	2.59E+10	0.00E+00	0.00E+00	0.00E+00
Transportation	0.00E+00	4.13E+10	3.36E+10	6.55E+10
Vegetables, Fruits and Plants	0.00E+00	5.17E+10	3.10E+10	0.00E+00
Increased ECI	**0.891**	**1.551**	**1.728**	**1.552**

Table 8c. Portfolio of Singapore (2021)

4.3 Sensitivity Analysis and Contingency Strategy

In the following section, our broad aim is to understand how sensitive Singapore is to changes in export in various industries. While the Economic Complexity Index has been shown to contain valuable information about the economic strength/capacity of a country, little has been said as to the stability of the measure itself. We seek to uncover the main drivers of stability under a country's ECI score and better understand longer-term projections for ECI growth. Additionally, gaining an intuition on the industries that are bolstering an economy and the industries that offer the greatest return per unit of investment is best done through visualization of industry-specific sensitivity. To this end, we have developed two categories of sensitivity analysis.

ECI Sensitivity Graph

First, in order to assess the effect particular industries have on each respective country, we developed ECI Sensitivity graphs (Figure 5). We use the shocking methodology to increment or decrement an industry's export level by a certain percentage and recalculate the ECI, all else being equal. While freezing the export dynamics of the rest of the world and enacting an instantaneous shock in export for a particular industry and country may not reflect real-life dynamics, what it does offer us is an understanding of a country's level of dependency on an industry in the context of ECI. The shocking is done in small percentage increments in order to smooth out the resulting curve. Additionally, a recurring theme one will see is that for most industries, a breaking point occurs where the ECI either jumps upwards or downwards, creating a hockey stick shape rather than a linear trend. While the inflection point may not be accurate in the context of real life, comparing the various inflection points across industries can give us valuable insight.

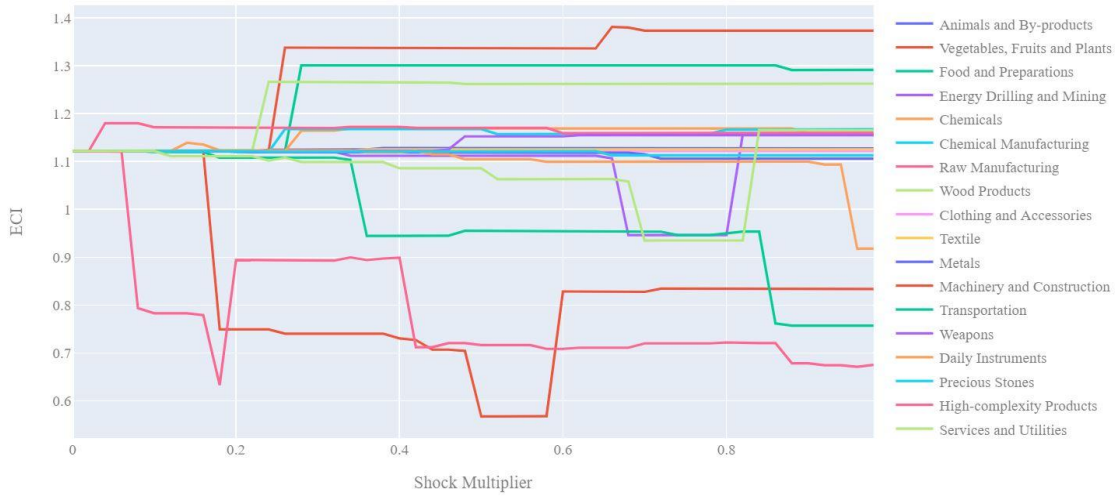


Figure 5. Sample ECI Sensitivity Graph (2018)

The graphs are formulated as follows. There are six ECI Sensitivity graphs, two for each of the following years: 2021, 2018, and 2013. The first chart, Incremental ECI Sensitivity, shows positive shocking in which export numbers are shocked upwards per industry. The

X-axis is in terms of percentage shock per current dollar value of export. The Y-axis is the recalculated ECI level post-shocking. The second chart, Decremental ECI Sensitivity, follows the same format except the X-axis represents negative shock. In other words, exports for each industry are decremented, and the ECI is accordingly recomputed.

SDV Sensitivity

Secondly, we analyze the sensitivity of the SDV to changes in export levels. The goal is to understand how export level changes for a particular industry can affect the marginal opportunity gain for other industries. We will be using specifically high-complexity products and food and preparations as our base industries. We will be increasing or decreasing the absolute export level in both of these industries and observing the effects on the SDV.

When the opportunity gain of an industry is negative, the SDV sensitivity approximates how an over-development of the industry jeopardizes the economic structure of a country. When the opportunity gain of the industry is zero, the SDV sensitivity determines whether the further development of the industry shapes the country with a better economic structure and predicts how the SDV would change accordingly. Specifically, as we reduce the export of such an industry to 25% - 50% of its original value, a few other industries originally with negative opportunity gain could likely become profitable.

Similar to the ECI sensitivity graphs above, we will be shocking the export of high-complexity products and food and preparations in small percentage increments. A new SDV, represented by a new column in the charts, is recorded only when a certain level of shock changes the structure of the SDV. In effect, we are incrementing or decrementing export levels of two industries until the marginal opportunity gain of any industry changes in category (positive, negative, or neutral). Below is an example of an SDV Sensitivity chart with Positive Shocking. Industries with positive marginal opportunity gain are colored blue, neutral is colored white, and negative is colored red.

	0.0%	10.0%	30.0%	50.0%	80.0%	100.0%	120.0%
0	Vegetables, Fruits and Plants	Vegetables, Fruits and Plants	Vegetables, Fruits and Plants	Chemicals	Chemicals	Chemicals	Machinery and Construction
1	Daily Instruments	Daily Instruments	Daily Instruments	Services and Utilities	Services and Utilities	Daily Instruments	Chemicals
2	Weapons	Weapons	Weapons	Textile	Textile	Textile	Daily Instruments
3	Transportation	Transportation	Transportation	Weapons	Daily Instruments	Services and Utilities	Services and Utilities
4	Machinery and Construction	Machinery and Construction	Machinery and Construction	Transportation	High-complexity Products	Transportation	Transportation
5	Metals	Metals	High-complexity Products	Machinery and Construction	Transportation	Chemical Manufacturing	Textile
6	High-complexity Products	High-complexity Products	Chemicals	High-complexity Products	Machinery and Construction	Weapons	Chemical Manufacturing
7	Chemicals	Services and Utilities	Services and Utilities	Daily Instruments	Chemical Manufacturing	High-complexity Products	Weapons
8	Services and Utilities	Chemicals	Textile	Chemical Manufacturing	Weapons	Machinery and Construction	High-complexity Products
9	Textile	Textile	Chemical Manufacturing	Precious Stones	Clothing and Accessories	Clothing and Accessories	Clothing and Accessories
10	Chemical Manufacturing	Chemical Manufacturing	Precious Stones	Clothing and Accessories	Precious Stones	Precious Stones	Raw Manufacturing
11	Precious Stones	Precious Stones	Clothing and Accessories	Vegetables, Fruits and Plants	Raw Manufacturing	Raw Manufacturing	Precious Stones
12	Clothing and Accessories	Clothing and Accessories	Raw Manufacturing	Raw Manufacturing	Wood Products	Metals	Wood Products
13	Raw Manufacturing	Raw Manufacturing	Metals	Metals	Metals	Wood Products	Metals
14	Energy Drilling and Mining	Energy Drilling and Mining	Energy Drilling and Mining	Wood Products	Energy Drilling and Mining	Energy Drilling and Mining	Energy Drilling and Mining
15	Wood Products	Wood Products	Wood Products	Energy Drilling and Mining	Animals and By-products	Animals and By-products	Animals and By-products
16	Animals and By-products	Animals and By-products	Animals and By-products	Animals and By-products	Vegetables, Fruits and Plants	Food and Preparations	Food and Preparations
17	Food and Preparations	Food and Preparations	Food and Preparations	Food and Preparations	Food and Preparations	Vegetables, Fruits and Plants	Vegetables, Fruits and Plants
ECI	2.261503667	2.520234671	3.08896214	3.452901685	4.299466299	4.439916975	5.069638102

Table 9. Sample Incremental SDV Sensitivity for High-Complexity Products (2018)

Contingency Plan

The Contingency Plan aims to present a set of solutions with respect to upheavals in different industries. Instead of compensating for the declining production directly, the best strategy is to develop those incipiently profitable industries. In this manner, we can derive a contingency strategy for countries to deal with possible abrupt declines of crucial industries. In some cases, the SDV remains unchanged even when a zero-opportunity-gain industry declines to 20% in terms of export. We can then conclude the industry is not indispensable to the country. As a clarification, the three consecutive N/As mean that the country doesn't even need to respond to a collapse in the industry. Countries tend to have distinct solutions to the ups and downs of the same industry. To create the contingency strategy table, we decrease the export level for each industry in the country's current production space by 60% respectively. The three highest-ranking industries in the new SDV are then returned.

Product Names	0	1	2
Animal and By-products	Services and Utilities	Daily Instruments	Weapons
Vegetables, Fruits and Plants	Services and Utilities	Daily Instruments	Weapons
Food and Preparations	Services and Utilities	Daily Instruments	Weapons
Energy Drilling and Mining	Services and Utilities	Daily Instruments	Weapons
Chemicals	Services and Utilities	Daily Instruments	Weapons
Chemical Manufacturing	Services and Utilities	Daily Instruments	Weapons
Raw Manufacturing	Services and Utilities	Daily Instruments	Weapons
Wood Products	Services and Utilities	Daily Instruments	Weapons
Clothing and Accessories	Services and Utilities	Daily Instruments	Weapons
Textile	Services and Utilities	Daily Instruments	Weapons
Metals	Services and Utilities	Daily Instruments	Weapons
Machinery and Constructions	Services and Utilities	Daily Instruments	Weapons
Transportation	Services and Utilities	Raw Manufacturing	Daily Instruments
Weapons	Services and Utilities	Daily Instruments	Transportation
Daily Instruments	Services and Utilities	Weapons	Transportation
Precious Stones	Services and Utilities	Daily Instruments	Weapons
Daily Instruments	Services and Utilities	Daily Instruments	Weapons
Services and Utilities	Daily Instruments	Weapons	Transportation

Table 10. Sample Contingency Strategy (2019)

4.3 Sensitivity Analysis Results and Interpretation

We examine Singapore's ECI Decremental and Incremental Sensitivity Charts for 2021. An increase in Food and Preparation will lead to the highest change in ECI, followed by High-complexity Products. The strong sensitivity effect of manipulating the high-complexity products and Transportation categories remains consistent with previous years. For the negative shock cases, chemical manufacturing becomes most impactful. The rest of the industries do not appear to have the same level of sensitivity.

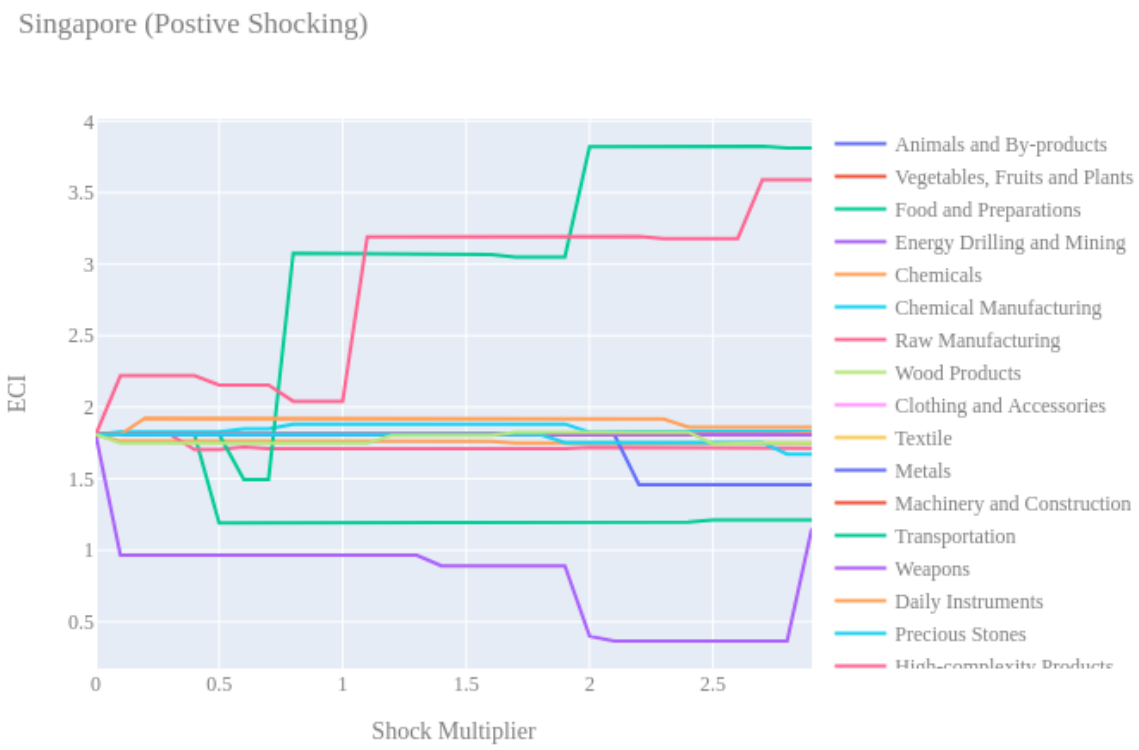


Figure 6a. Incremental ECI Sensitivity for Singapore (2021)

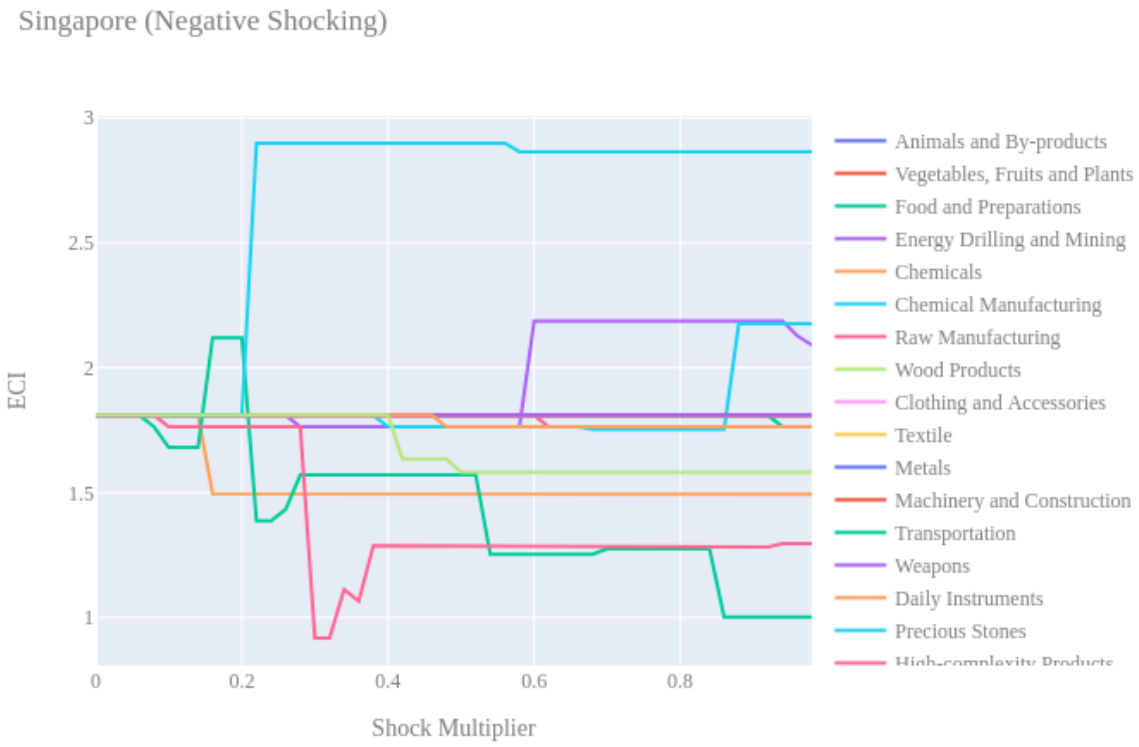


Figure 6b. Decremental ECI Sensitivity for Singapore (2021)

Below, we consider Singapore's 2018 Negative Shock chart. We can see that Singapore is highly sensitive to High Complexity Products, Transportation and Machinery. This is expected from a well-diversified, developed country. Additionally, decreases in export of Energy & Drilling, Services and Utilities and Chemicals seem to increase the overall ECI score.

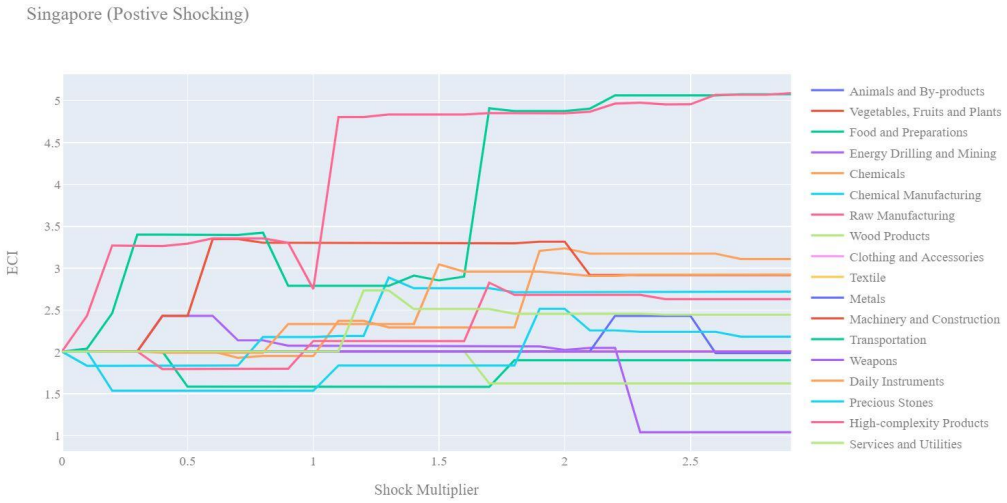


Figure 7a. Incremental ECI Sensitivity for Singapore (2018)

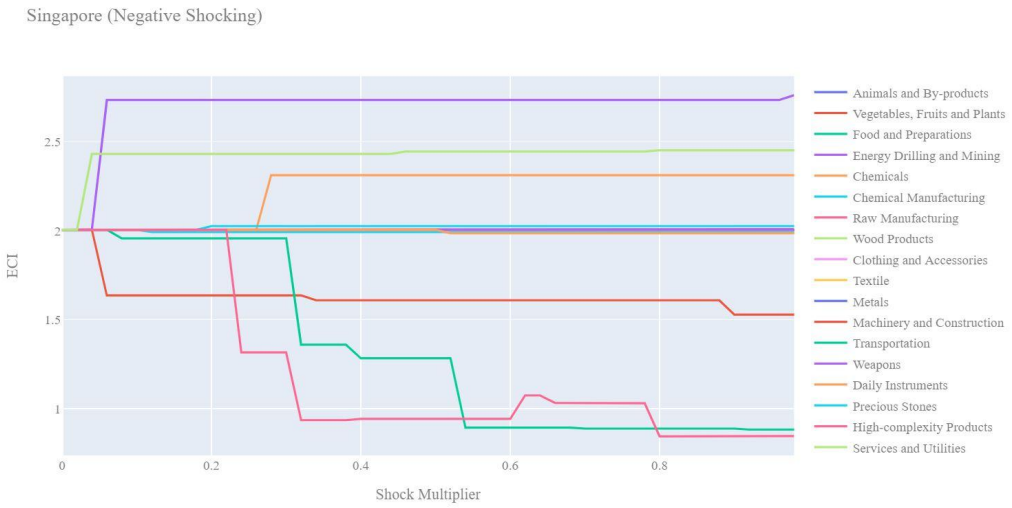


Figure 7b. Decremental ECI Sensitivity for Singapore (2018)

Next we consider the 2013 ECI Sensitivity graphs. We see that in the positive shocking case most industries giver either no benefit or cause drawdowns in the ECI. However increased export of High Complexity Products can lead to higher ECI but over 250% increase in export is required.

In the 2013 negative shocking case, we see that again Singapore is marginally less sensitive to downturns than in the 2018 sensitivity profile. This suggests that Singapore has become more sensitive to export downturns in High Complexity Products and Transportation in the recent past as their economy begins to rely more heavily on these industries to bolster their ECI score.

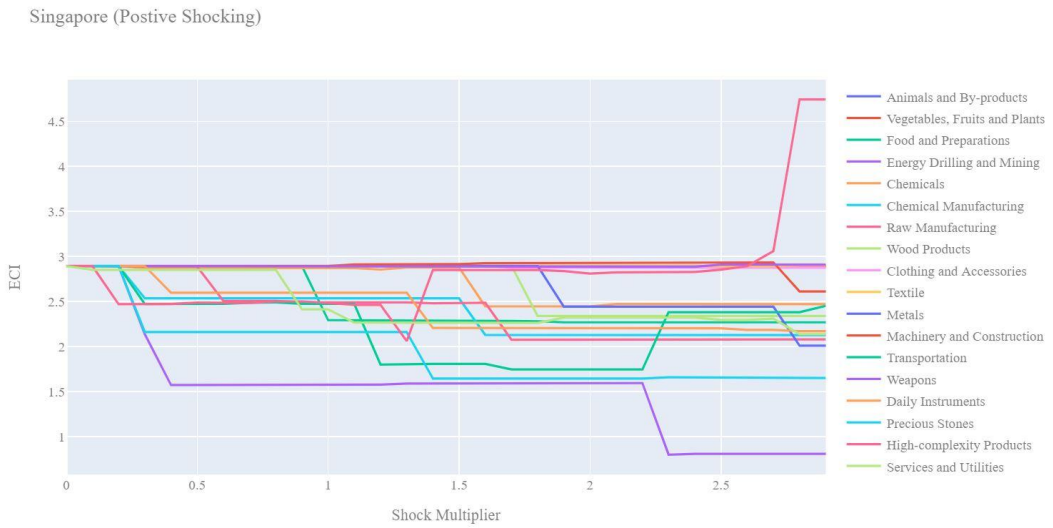


Figure 8a. Incremental ECI Sensitivity for Singapore (2013)

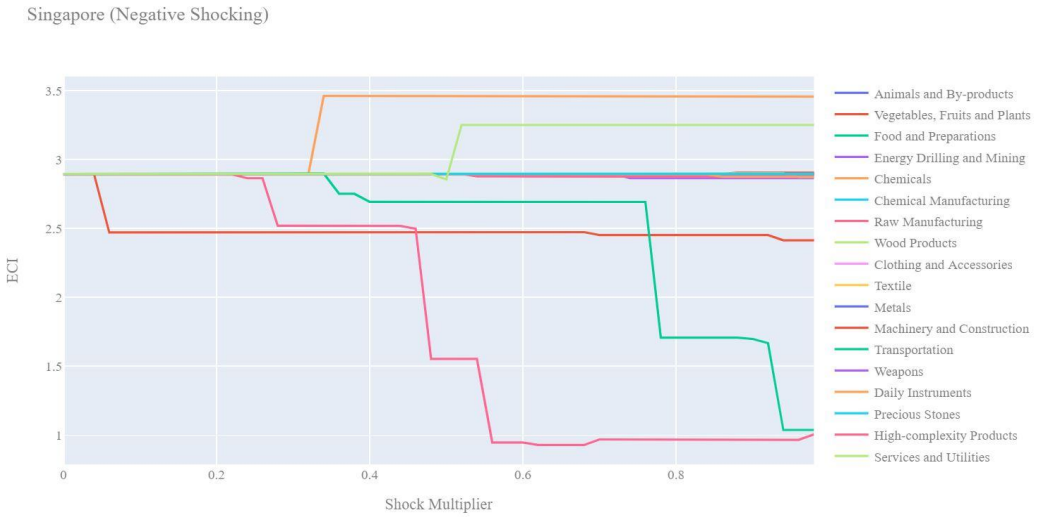


Figure 8b. Decremental ECI Sensitivity for Singapore (2013)

Below we see the SDV sensitivity charts for High Complexity Products (Table 11). We see that fairly small decreases in export of High Complexity Products makes room for other industries to shift from the negative opportunity gain to neutral opportunity gain territory. No industries become immediately attractive after a drawdown of High Complexity Products.

Considering the positive SDV sensitivity chart we observe that as exports of High Complexity products increases industries that were not worth investing begin to shift to the positive opportunity gain region. Intuitively as High Complexity Products become a stronger industry for Singapore, other industries start to become viable industries to pursue.

Rank	Incremental	Decremental
1	Machinery and Construction	Vegetables, Fruits and Plants
2	Chemicals	Services and Utilities
3	Daily Instruments	Energy Drilling and Mining
4	Services and Utilities	Precious Stones

5	Textile	Daily Instruments
6	Transportation	Transportation
7	Chemical Manufacturing	Machinery and Construction
8	Weapons	Food and Preparations
9	High-complexity Products	Raw Manufacturing
10	Clothing and Accessories	Chemical Manufacturing
11	Raw Manufacturing	Chemicals
12	Precious Stones	High-complexity Products
13	Wood Products	Textile
14	Metals	Weapons
15	Energy Drilling and Mining	Clothing and Accessories
16	Animals and By-products	Metals
17	Food and Preparations	Wood Products
18	Vegetables, Fruits and Plants	Animals and By-products
ECI	**4.804992937**	**0.843364788**

Table 11. Singapore's SDV Sensitivities for High-complexity Products (2018)

Below we see the SDV sensitivity charts for Food and Preparations. As expected for a developed country, Singapore is not very sensitive in both the positive shocking and negative shocking case to Food and Preparations. The country's SDV is largely unaffected by this particular industry.

Rank	Incremental	Decremental
1	Vegetables, Fruits, and Plants	Vegetables, Fruits, and Plants
2	Services and Utilities	Transportation
3	Transportation	Machinery and Construction
4	Machinery and Construction	Food and Preparations
5	Energy Drilling and Mining	High-complexity Products
6	High-complexity Products	Energy Drilling and Mining
7	Chemicals	Chemicals
8	Textile	Services and Utilities
9	Daily Instruments	Daily Instruments
10	Chemical Manufacturing	Textile
11	Weapons	Chemical Manufacturing
12	Clothing and Accessories	Weapons
13	Raw Manufacturing	Clothing and Accessories
14	Precious Stones	Precious Stones
15	Wood Products	Raw Manufacturing
16	Metals	Wood Products
17	Animals and By-products	Metals
18	Food and Preparations	Animals and By-products
ECI	**2.005369933**	**1.90194945**

Table 12. Singapore's SDV Sensitivities for Food and Preparations (2018)

4.4 Contingency Strategy

Decreasing export of each industry in [Country]'s current production space by 60% respectively, we derive the contingency strategy shown below.

Product Names	0	1	2
Animal and By-products	Machinery and Construction	Chemical Manufacturing	Services and Utilities
Vegetables, Fruits and Plants	Machinery and Construction	Chemical Manufacturing	Services and Utilities
Food and Preparations	Machinery and Construction	Chemical Manufacturing	Services and Utilities
Energy Drilling and Mining	Services and Utilities	High-complexity Products	Precious Stones
Chemicals	Chemicals	Chemical Manufacturing	Machinery and Construction
Chemical Manufacturing	Machinery and Construction	Chemical Manufacturing	Services and Utilities
Raw Manufacturing	Machinery and Construction	Chemical Manufacturing	Services and Utilities
Wood Products	Machinery and Construction	Chemical Manufacturing	Services and Utilities
Clothing and Accessories	Machinery and Construction	Chemical Manufacturing	Services and Utilities
Textile	Machinery and Construction	Chemical Manufacturing	Services and Utilities
Metals	Machinery and Construction	Chemical Manufacturing	Services and Utilities
Machinery and Construction	Machinery and Construction	Chemical Manufacturing	Services and Utilities
Transportation	Services and Utilities	Daily Instruments	High-complexity Products
Weapons	Machinery and Construction	Chemical Manufacturing	Services and Utilities
Daily Instruments	Machinery and Construction	Chemical Manufacturing	Services and Utilities
Precious Stones	Machinery and Construction	Chemical Manufacturing	Services and Utilities
High-complexity Products	Services and Utilities	Transportation	Precious Stones
Services and Utilities	High-complexity Products	Services and Utilities	Machinery and Construction

Table 13. Singapore's Contingency Strategy (2018)

5. Macro-level Predictions

5.1 Structural Optimality Index

ECI sensitivity described in the section before has proven to be a significant factor in deciding the economic outcomes of countries. In order to quantitatively evaluate how effective our development strategies are and how deviations from the suggested developmental path will lead to suboptimal growth results, we define the measure – Structural Optimality Index (SOI) – on a country level as the Adjusted R-Square obtained from regressing the country's realized industry development over the suggested development strategy. Both strategies are quantified in nature, with the realized development represented by increasing export in every major industry group and the suggested development strategy represented by the opportunity gains of developing the corresponding industry groups as calculated in previous sections. The adjusted R-square from the regression thus provides us with a quantified measure of how the development path adopted by the country has fitted with/differed from calculations on a complexity level.

After obtaining this measure for all countries in our database, we further regress countries' five-year economic growth, which is defined as the percent increase in GDP (USD), over their SOI. Figure 9 illustrates the regression output, which shows a strong positive correlation between countries' SOI and their five-year GDP growth, significant at the 1% level and achieving an adjusted R^2 of 0.045%. In other words, the more a country develops as suggested by calculations on a complexity level, the better economic outcomes it achieves.

Table 14: OLS Regression Results	
Dep. Variable: GDP	**F-Statistic:** 5.963
R^2: 0.054	**Prob (F-Stat):** 0.0163
Adj R^2: 0.045	**No. Observations:** 106

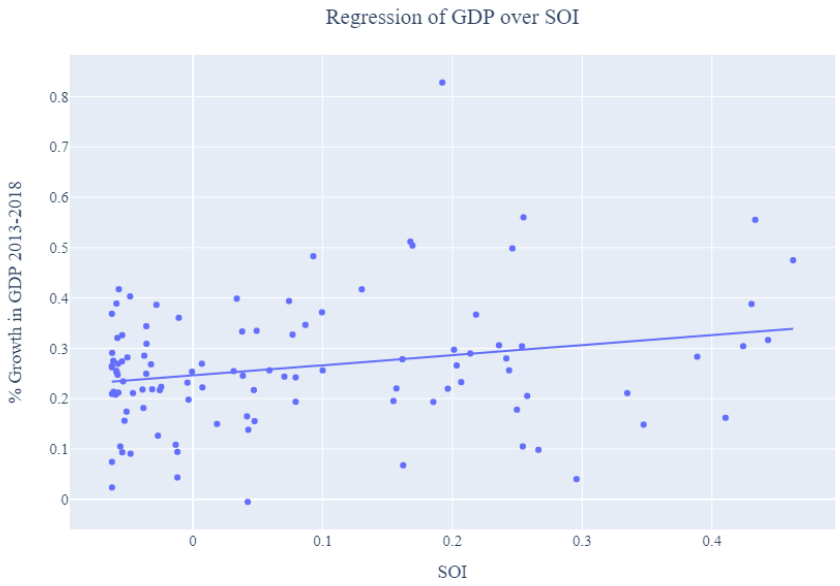


Figure 9. Regression of Five-Year GDP Growth over SOI (2013-2018)

5.2 SOI of Singapore and Its Implications

Singapore, for instance, has a relatively low level of structural optimality as compared with its peers. As the regression in Figure 7 suggests (the orange curve represents export increase and the blue curve stands for opportunity gain of the corresponding industry), Singapore demonstrates a low level of correlation with the suggested developmental path, having an adjusted R-square of around -5.1% and a 5-year growth rate of 28.2%. Here the SOI underestimates the expected growth of the country. This is in direct contrast to emerging economies such as Turkey, where there is a high SOI of around 21.8% and a corresponding 5-year GDP growth of 36.7%, making it one of the fastest developing economies during the period. In sum, Singapore's stagnant economic progress from 2013 to 2018 can be at least partially explained by a mismatched development strategy that demonstrates a considerable level of deviations from our suggested developmental path. In specific, Singapore invested heavily in the Transportation industry, while it should have focused more on industry groups such as Machinery and Construction.

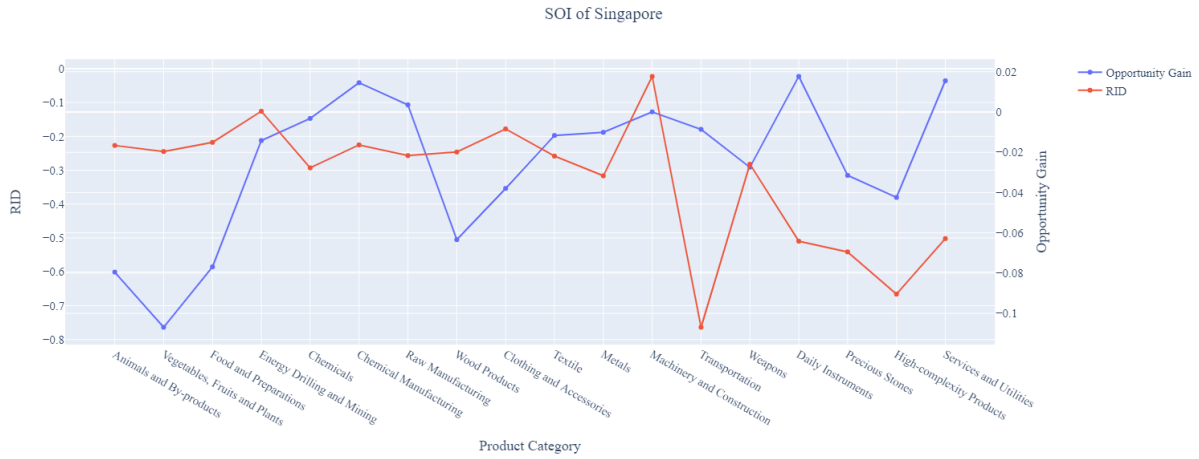


Figure 10a. SOI of Singapore (2013-2018)

For the 2019-2021 years, Singapore has a strong presence in the Weapons and Energy Drilling and Mining industries. The weapons industry seems to be overdeveloped when considering their lower opportunity gain relative to RID but Energy Drilling and Mining still presents a good opportunity for further investment. It also could consider investing in Precious Stones and Chemical Manufacturing to improve its growth. Singapore has seen a growth in GDP over those three years of 5.87%, with an average growth of 2.31%, compared to 3.6% for the average yearly growth for the five years prior.

Higher than before, its adjusted R-squared value of 0.391 now indicates a high correlation between the GDP growth and the implemented development path. Progress is slow on a global scale during this period, but Singapore demonstrates a greater ability to adjust to negative economic shocks by improving SOI and increasing GDP growth than it did between 2013 and 2018.

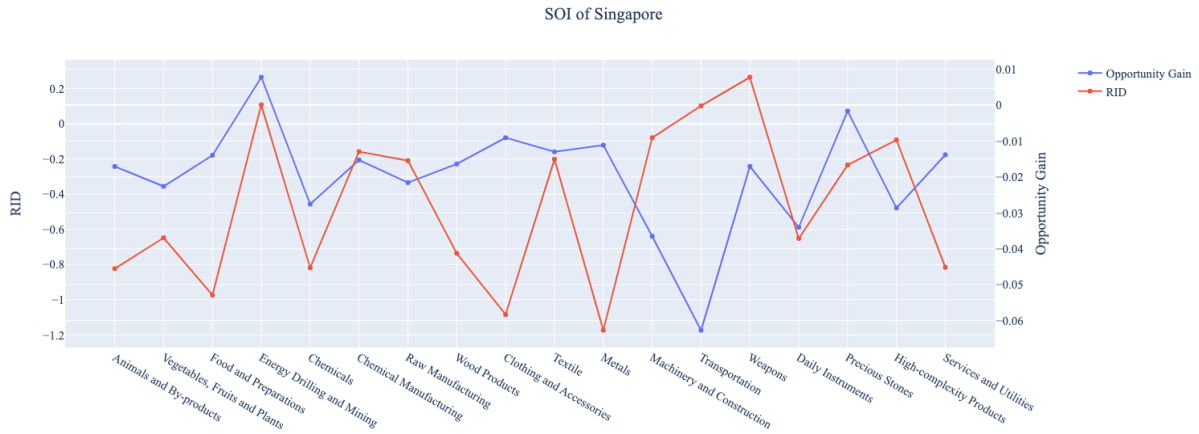


Figure 10b. SOI of Singapore (2019-2021)

6. Concluding Remarks

In conclusion, Singapore has demonstrated a low level of economic growth in terms of GDP during the period from 2013 to 2018, concurrent with a stagnation in economic complexity as compared with other major Asian economies.

The level of economic progress during the period, we believe, can be partially explained through analysis of the economic and product complexity structure of Singapore on the industry group level. The product classification system we adopt allows us to measure the realized industry development for various industry groups and to observe that Singapore invested heavily in developing Transportation, High-complexity Products during the period.

Based on our analysis of the opportunity gain and a sensitivity analysis of major industry groups, Singapore can further its gains by prioritizing Chemicals, Machinery and Construction. We further note that Singapore has a slightly mismatched development strategy that indicates a moderate level of structural optimality on the complexity level, having an adjusted R-square of around -5.1%. Since a significant positive correlation exists between five-year GDP growth and the structural optimality index of an economy as we define and calculate, Singapore indeed has a suboptimal growth experience as compared with fast-growing economies both on a regional scale and on a global scale, and has the potential to further its economic gains through industrial structure optimization as suggested in the paper.

During the second examined period from 2019 to 2021, Singapore performed much weaker than before and compared to other countries, such as Indonesia and China. We infer that during the COVID-19 period, Singapore focused on developing Weapons and Energy Drilling and Mining industries despite a lower demand for these industries given the global economic downturn. We also note that Singapore has increased its investment in the sectors identified earlier, leading to a strong boost from Machinery and Construction industries, leaving some room for strategic improvement. The ECI suggests that greater growth could have been achieved through Precious Stones followed by High Complexity Products and Energy Drilling and Mining. The surprising growth also increased the adjusted R-squared value to 39.1% in 2021 from -5.1% in 2018, demonstrating the pursued strategies contributed to the GDP. With the revised focus, Singapore has further potential to advance its economic growth to maintain its position among other countries to continue its post-pandemic recovery.

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