Networks in Growth: Product Space, Small World Networks, and Growth Acceleration.

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Abstract

Is there a way to kindle acceleration in the economic growth rate of a country? What role do trade and comparative advantage play in this process? On the first question, prior work has examined "growth acceleration" episodes, finding them highly unpredictable. The vast majority of growth accelerations are unrelated to standard determinants such as political change and economic reform, and most instances of economic reform do not produce growth acceleration. This leads to a conundrum. Are growth accelerations idiosyncratic and/or a matter of luck? This paper uses a novel, network-based approach to international trade to make progress in decoding the mystery of growth acceleration.

Detailed product-level data on global trade enables measurement of the relatedness among products based on the pattern of revealed comparative advantage in world trade. Prior research has used this to infer how likely it is for different products to be exported together from the observable export-mix in the data. This network of relatedness among products is called "product space." We explicitly adopt a network interpretation of product space and use methods from the

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recent literature on complex networks to unravel the mystery behind the mechanics of growth acceleration.

One of the general results of the network literature is that "successful" high-performance networks in many settings have the "small world" property, combining high clustering of nodes with short path length across the network. This can create strong spillovers between nodes coupled with the potential for long range leaps across the network. Both features are advantageous in the context of economic growth. Could it be that the key to growth acceleration is whether the pattern of product specialization of a country develops a "small world" topology before the take-off? If true, then this implies that the country's location in product space and its pattern of product specialization matter for its likelihood of experiencing growth acceleration. We marshal evidence for this insight in the paper.

1 Introduction

Until quite recently, few relationships enjoyed as much consensus among economists as that between trade and growth. The view that integration into the global economy is a reliable way for countries to grow permeated advice from multilateral institutions such as the World Bank, the IMF, the OECD, as well as discussions by many distinguished economists (Krueger, 1998; Stiglitz, 1998; Fischer, 2000, for example). This view was supported by an influential body of research, the best known of which are papers by Dollar (1992), Sachs and Warner (1995), Ben-David (1993), and Frankel and Romer (1999). However, the consensus has been thrown into disarray due to criticism of this literature over problems in measuring openness, the statistical sensitivity of the specifications, the collinearity of protectionist policies with other bad policies, and other econometric difficulties (Rodriguez and Rodrik, 2000; Harrison and Hanson, 1999). As a result, there is now scepticism regarding the existence of a general, unambiguous relationship between openness and growth. Focus has shifted to a scrutiny of the channels through which trade openness may influence economic performance, and the way in which the relationship between trade and growth is contingent on country and external characteristics. A recent attempt to update the Sachs and Warner approach by Waczairg and Welch (2008) notes that while the evidence paints a favorable picture of outward-oriented policy reforms on average, it cautions against one-size-fits-all policy that disregards local circumstances.

In this paper, we apply a network approach to the comparative advantage of nations and discover that there may yet be a general pattern in the paths taken by countries which have experienced accelerations in their growth rate. Following recent work by Hausman and Bailey (2007) and Hidalgo et. al. (2007), we use detailed product-level data from the NBER World Trade Database to measure relatedness among products based on the pattern of revealed comparative advantage in world trade, indicating how likely it is for different products to be exported together from the observable export-mix in the data. This network of relatedness among products is called "product space." It seems natural to interprete "product space" in terms of a network. We therefore adopt a network interpretation of product space here, enabling us to draw upon analytical methods from the recent literature on complex networks[1].

One of the general results of this literature is that high performance networks in many settings (biological, technological, social, economic) have the "small world" property (Watts and Strogatz, 1998). In other words, in many contexts, the small world seems to be an "optimal" topology. A small world (SW) is a network whose topology combines high clustering among nodes with high connectivity (short path length) across nodes. Due to high clustering, such networks are likely to have strong spillovers between nodes (here, products), and short path length provides the potential for long range leaps across the network (to new products). Both features are advantageous in the context of economic development and growth. Could it be that the key to growth acceleration is whether the pattern of product specialization of a country (as reflected in its export basket) develops a "small world" topology before the take-off? This configuration could come about because product space and the pattern of product specialization of a country, which are both evolving over time, intersect so as to create conditions approximating a small world network. If true, then this implies that a country's location in product space and its pattern of product specialization matter for its likelihood of experiencing a growth acceleration. If we can find evidence for this line of reasoning, then we will have made important progress in decoding the mystery of growth acceleration and its relationship to trade and comparative advantage. Examining this insight is the primary goal of this paper.

Why should a small world network in product space facilitate rapid economic growth? The economic intuition is straightforward. Clustering of products enables economies of scale and scope and other agglomeration externalities. Short path length in the network allows "leaps" across product

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[1] Newman (2000) and Albert and Barabasi (2002) are good overviews of this literature. The survey by Jackson (2006) is a good introduction to the economics of networks.

space to higher-income products. The extent of scale and scope economies determine cost reductions, leading to savings and investment. Investment capabilities in turn determine how far a country can leap. Proximity in product space determines how far a country needs to leap to reach higher-income products. The relationship between clustering and network distance in product space thus plays a role in determining the likelihood of a leap to a higher growth path. We present a simple formalization of this intuition in a model below. These arguments are closely related to the literature on successful industrial districts (such as Silicon Valley as studied by Saxenian, 1994 and Castella et. al., 2000) or city growth (Jacobs, 1984; Glaeser et. al., 1992).

A summary of our methodology and findings is as follows.

1. First, we chart the topology of product space across time, from 1965 to 2000. This provides us with evidence that the product space network of relatedness among products based on the pattern of revealed comparative advantage in world trade has evolved considerably over this period. We find that the evolution of product space experienced a structural break during the 1980's.

2. Second, we map the product specialization pattern of individual countries in our dataset over the period 1965-2000. We then superimpose country-level product specialization on to the (global) product space network. Superimposing the country-level product specialization "sub"-network on the larger product-space network enables us to identify network properties of country-level product specialization . From this we obtain measures of network spillovers and distance, in accordance with our small world conjecture. We argue that countries which experienced episodes of growth acceleration had an overlap between their product specialization pattern and product space which provided a combination of high spillovers between current products and short network distance to potential new products prior to growth acceleration, while countries which failed to experience subsequent growth acceleration did not. In other words, countries that subsequently experienced growth acceleration had an intersection between their product specialization pattern and product space that created propitious conditions. They were, 'in the right space at the right time.'

3. Third, we run multivariate regressions to examine if there is large sample support for the hypothesis that if a country's pattern of product

> specialization possesses high spillovers between current products and low network distance to potential new products – resembles a small world – then it is more likely to experience subsequent growth acceleration. We find that our network measures work well in predicting a heightened probability of experiencing subsequent growth acceleration. [More details on econometric results to go here].

Our ability to bring a network approach to bear upon these issues builds on recent work on comparative advantage, trade and growth by Hausman and Bailey (2007), Hidalgo et. al. (2007) and Hausman, Pritchett and Rodrik (2006). Hidalgo et. al. (2007) map product space (footnote: only for 2000) and ask if the pattern of product specialization of a country is densely or sparsely connected. They identify two patterns here. First, the pattern of relatedness of products exhibits a high degree of heterogeneity: there are parts of the product space that are dense while others are sparse. More sophisticated products are located in a densely connected core while less sophisticated products occupy a less-connected periphery. Second, changes in the revealed comparative advantage of nations are governed by the pattern of relatedness at a global level. Empirically, countries move through the product space by developing goods close to those they currently produce. This implies that countries that are specialized in a dense part of the product space have an easier time at changing their revealed comparative advantage than countries that are specialized in more disconnected products. Most countries can reach the core only by traversing empirically infrequent distances, which may help explain why poor countries have trouble developing more competitive exports and fail to converge to the income level of rich countries. The inability to make long-range leaps is associated with difficulty in moving from low-growth (traditional/poor) products to high-growth (modern/rich) products. Countries that have a comparative advantage in traditional products are likely to be stuck in a "product-trap," since they will only be able to produce products close to the ones they already produce. According to this view, a country's location in product space is a key determinant of its growth capabilities.

A separate paper by Hausman, Pritchett and Rodrik (2005) examines "growth accelerations," episodes of rapid acceleration in economic growth that are sustained for at least eight years, and finds them to be highly unpredictable[2]. The vast majority of growth accelerations are unrelated to

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[2] Growth accelerations are defined as rapid growth episodes that satisfy the following conditions: (i) per-capita income growth $\geq 2\%$ per year, (ii) the increase in growth has to be sustained for at least 8 years, (iii) the post-acceleration growth has to be at least

standard determinants such as political change and economic reform, and most instances of economic reform do not produce growth accelerations. This leaves us with a conundrum. Are growth accelerations idiosyncratic and/or a matter of luck? The implications of such a conclusion would be distressing, to say the least. But while the mechanics of these transitions continue to be a mystery, the good news is that Hausman et. al. find that growth accelerations are a fairly frequent occurrence. Of the 110 countries in their sample, 60 have had at least one acceleration in the 35-year period between 1957 and 1992 – a ratio of 55 percent.

By bringing a network approach to product space and then using these measures to explain growth acceleration, we bring these two strands of research together, and, we hope, provide a distinct and valuable contribution to the literature on trade and economic growth. We believe that the network-based methodology unravels characteristics of the growth acceleration process that are difficult to both see and understand using conventional approaches. In the next section we explain our hypothesis and the network approach in more detail. In section 3 we present a simple theoretical framework to ground our empirical analysis. Section 4 outlines our empirical analysis thus far and subsequent steps in the research program. Section 4 discusses broader implications of the research project and concludes.

2 Product Space, Country Specialization, and the Small World

Product Space

We follow Hidalgo et. al. (2007) and Hausman and Bailey (2007) in computing the product space of relatedness among products based on the pattern of revealed comparative advantage in world trade. We provide a brief description here; the reader is referred to their papers for more detail. Like them, we use the NBER World Trade Database for the computation of product space (Feenstra et al., 2005).

The first step is the computation of "revealed comparative advantage" (RCA), which measures whether a country c exports more of good i, as a share of its total exports, than the "average" country (i.e., $RCA > 1$ not

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3.5% per year, and (iv) post-acceleration output has to exceed the pre-episode peak level of income, to rule out cases of pure recovery.

RCA<1).

$$RCA_{c,i} = \frac{\frac{x(c,i)}{\sum_i x(c,i)}}{\frac{\sum_c x(c,i)}{\sum_{c,i} x(c,i)}} \tag{1}$$

RCA, thus computed, is then used to compute "proximity" between products, which formalizes the intuitive idea that the ability of a country to produce a product depends on its ability to produce other related products. If two goods are related because they require similar institutions, infrastructure, resources, technology, or some combination thereof, they will likely be produced in tandem, whereas dissimilar goods are less likely to be produced together. Formally, the proximity ϕ between products i and j is the minimum of the pair-wise conditional probabilities of a country exporting a good given that it exports another:

$$\phi_{i,j} = \min\{P(RCAx_i|RCAx_j), P(RCAx_j|RCAx_i)\} \tag{2}$$

The matrix of these proximities characterizes product space. We compute the proximity matrix for every year between 1965 and 2000. These matrices can be compared to understand how product space has evolved during this period. The proximity matrix can be considered a complex network[3], where each product represents a node in the network while the edges between them and their intensities are denoted by the proximities between the products. Given the symmetry of the proximity matrix, the network resulting from it can be characterized as a weighted, undirected network. This perspective then allows us to analyze product space and its evolution in terms of the properties of the network.

Country Level Product Specialization

The set of products for which a country possesses RCA (>1) is what we refer to as country level product specialization. This is essentially the comparative advantage of a country. We can examine how this set has changed over the time period of our data for countries which experienced growth acceleration and those that did not.

The Small World Hypothesis

A network exhibits small-world (SW) characteristics if, roughly speaking, any two nodes in the network are likely to be connected through a short

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[3] Complex networks are large scale graphs that are composed of so many nodes and links that they cannot be meaningfully visualized and analyzed using standard graph theory. Recent advances in network research now enable us to analyze such graphs in terms of their statistical properties. Albert and Barabasi (2002) and Newman (2003) are excellent surveys of these methods.

sequence of intermediate links. This can come about via a combination of short characteristic path length and high clustering in the network. The clustering coefficient of a network is a measure of the cliquishness of nodes, and the characteristic path length is a measure of the average number of links connecting any two nodes. Recent work has suggested that the phenomenon is pervasive in networks arising in nature (Watts and Strogatz, 1998; Watts, 2004; Albert and Barabasi, 2002, Goyal et. al, 2006). Virtually all known complete networks in nature, such as the network of scientific collaborations, the power grid of the U.S., and the neural network of the earthworm, are small world networks. These findings fuel the conjecture that the small world may be an “optimal” topology for successful (high performance) networks in nature[4].

We conjecture that if we were to superimpose country level product specialization on product space, we would find that the pattern of product specialization displays small world characteristics for countries which experienced growth accelerations, prior to their take-off. Conversely, countries which did not experience growth accelerations did not see their country level product specialization pattern resemble a small world. Thus, our key hypothesis is that if a country’s pattern of product specialization resembles a small world, then it is more likely to experience subsequent growth acceleration.

If product space is changing over time (due to changes in technology, preferences and other effects), then a country with a particular pattern of product specialization might find that the product space has moved to a configuration that creates advantageous conditions for product leaps and thus faster growth. It could also be that both product space and the country-level patterns of product specialization have changed over time. Thus product space and country-level product specialization could have co-evolved to intersect in such a way as to create a “small world” and enable product leaps. According to this view, we could say that the key to growth acceleration is thus essentially a matter of being “in the right space at the right time.” We aim to test this hypothesis here.

3 A Model

We present a simple theoretical model here to formalize the intuition for why a country should experience a greater likelihood of growth acceleration

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[4] There is now a large literature on these networks. See Newman, Albert and Barabasi, Jackson in the references.

if its pattern of product specialization resembles a small world network in product space.

The countries that are the focus of our study are all lower income developing countries, without dominant global market share in any product. Hence we consider them price-takers on the global market, similar to the familiar "small open economy" assumption in international macroeconomics. We also assume that access to financial markets to finance expansionary activities is not available to firms. This seems a reasonable assumption since the countries that are the focus of our inquiry are mostly low income with poorly developed financial markets.

At time $t = 1$ country x has RCA in a set of products, $R = \{y_1, y_2, ...y_{n1}\}$. Set R can be referred to as the pattern of product specialization for country x. Production takes place in firms, which produce one unit of a unique product in each period. Each product faces a world price of p_{y_i}. The cost of production for a particular product is affected by positive spillovers from the other products in which the country has RCA. The magnitude of the spillover is increasing in the proximity of the other products to the product in question. The proximity measure between product y_i and y_j is ϕ_{ij} and captures fixed investments, shared know-how, and other synergies between the two products. Thus we let the cost of production for y_i be $c_{y_i} = c(\sum_{j,j\neq i}^{n_1} \phi_{ij})$. Assume $c' < 0, c'' < 0$, and $c(0) = \bar{c}$.

The ϕ_{ij}'s thus define a weighted network between the products that country x has in its RCA set. Let $g_i = (\phi_{i1},...\phi_{ii-1},\phi_{ii+1},..., \phi_{in1})$, and the network of relatedness among products for country x is $g = (g_1, g_2, ..., g_{n1})$. Let $S_i = \sum_j g_i$ represent spillovers that benefit product i. Then $c_{y_i} = c(S_i)$.

A firm can attempt to "leap" to another product in product space that is not currently within set R and develop RCA is this new product. If the products are all indexed numerically, then we can say this implies a leap to a product in the set $\Delta = \{y_{n2}, y_{n3}, ...y_N\}$ where product $n_2, n_{3..}$ stand for products numerically indexed after n_1, which is the 'last' product in the RCA set R of country x as described above. N is the total number of products in product space. However, moving to a different product is costly. Assume for simplicity that the cost of moving to new products, for each unit distance in product space is θ. In addition, in the period immediately after leaping to a new product, there are no spillovers from other products. These spillovers, develop by the following period, and depend upon the production cluster associated with the new product.

There are three periods. Production takes place in all three periods, but consumption/utility is realized only at the end of period three.

The firm's profit at $t = 1$ is $\pi^1 = p_{y_i} - c(S_i)$.

In period 2 the firm can choose to make a leap to a nearby product. Say the distance in product space to the nearest product not in R is $\underline{d}$. If the firm uses its period 1 profits to make a leap, the furthest it can go is $\frac{\pi^1}{\theta} = d$. If $d \geq \underline{d}$, then the leap is feasible. In other words, a necessary condition for a leap to a new product in period 2 is,

$$\pi^1 = p_{y_i} - c(S_i) \geq \theta \underline{d}. \tag{3}$$

The amount $\theta \underline{d}$ could be interpreted of as the cost of fixed investments associated with moving into the new product.

Now suppose the price for the nearest product (k) is p_{y_k}.

If the firm leaps to product k then period 2 profits are $\pi^2 = p_{y_k} - \overline{c}$.

For a firm which has leaped to a new product in period 2, period 3 profits are $\pi^3 = p_{y_k} - c(S_k)$, where $S_k = \sum_{j,j \neq k}^{n_k} \phi_{kj}$ represents the spillovers for product k associated with the new RCA set for country x, call this R'.

We can then outline three possible production scenarios for a country. Parentheses indicate time periods.

Scenario I, Growth Acceleration: ($t = 1$) Original Product — ($t = 2$) New Product — ($t = 3$) New Product.

Payoff $\Pi(I) = p_{y_i} - c(S_i) + p_{y_k} - \overline{c} + p_{y_k} - c(S_k)$

Scenario II, Stagnation: ($t = 1$) Original Product — ($t = 2$) Original Product — ($t = 3$) Original Product.

Payoff $\Pi(II) = 3(p_{y_i} - c(S_i))$

Scenario III, Slow Growth: ($t = 1$) Original Product — ($t = 2$) Original Product — ($t = 3$) New Product.

Payoff $\Pi(III) = 2(p_{y_i} - c(S_i)) + p_{y_k} - \overline{c}$

Scenario I is akin to "growth acceleration," Scenario II is "stagnation," and III is "slow growth."

From this setup we can see that there are a couple of issues that will come into play in determining whether a country will make a leap, and thus whether we will observe Scenario (I). There are both demand side (price) and supply side (cost) factors involved. If the move is to more "upscale" products, with higher prices, i.e., $p_{y_k} > p_{y_i}$, then, other things being equal, the transition is more likely. If the production cluster associated with the new product is more connected, with consequently greater spillovers on the cost side, i.e., $S_k > S_i$, then, other things being equal, the transition is more likely.

To see the tradeoffs more clearly, subtract Scenario (II) payoff from Scenario (I) payoff.

$$\Pi(I) - \Pi(II) = 2(p_{y_k} - p_{y_i}) - (\overline{c} - c(S_i)) - (c(S_k) - c(S_i)) \tag{4}$$

Call this the "leap-incentive" condition. The second term is the period 2 increase in cost due to the leap and the third term is the period 3 decrease in cost after the leap. We can see from this that ceteris paribus, a high level of spillovers in period 1 (high S_i) can reduce the incentive to leap because of the period 2 increase in cost (which could be high) and the period 3 decrease in cost (which could be low). Condition (4) can also be written as,

$$\Pi(I) - \Pi(II) = 2(p_{y_k} - p_{y_i}) - \overline{c} + 2c(S_i) - c(S_k) \tag{5}$$

which is decreasing in current spillovers (S_i), increasing in potential spillovers (S_k), and increasing in the price premium of potential products over current products, ($p_{y_k} - p_{y_i}$).

At the same time however, high period 1 spillovers (S_i) makes it easier to satisfy (3), the "leap-feasibility" condition. Thus, while potential spillovers (S_k) increase the likelihood of growth acceleration, the impact of current spillovers (S_i) seems a priori ambiguous. Ultimately, whether current spillovers have a positive or negative influence on the likelihood of a growth acceleration depends respectively upon whether (3) or (4) is binding. (3) can be considered the "supply-side" and (4) the "demand-side" of the growth acceleration problem as framed here.

In order to see how these two constraints interact consider the following.

Rewrite the leap-incentive condition (5) as an implicit function $I(S_i, S_k) \equiv 2(p_{y_k} - p_{y_i}) - \overline{c} + 2c(S_i) - c(S_k) = 0$. Then we can obtain $\frac{\partial S_k}{\partial S_i} = -\frac{I_{S_i}}{I_{S_k}} = \frac{2c'(S_i)}{c'(S_k)} > 0$.

The boundary of the leap-feasibility condition (3) is $F \equiv \pi^1 = 0$. This implies $c(S_i) = p_{y_i} - \theta \underline{d}$. Label this value of S_i as S_i^*.

Using this value of S_i^* in $I(S_i, S_k) = 0$ yields $c(S_k^*) = 2(p_{y_k} - \theta \underline{d}) - \overline{c}$.

We can represent conditions $F = 0$ and $I(S_i, S_k) = 0$ in the following figure. Both feasibility and incentive constraints for growth acceleration are satisfied in the shaded region. The size of this region thus represents the likelihood of growth acceleration.

[Figure 1 here]

Comparative Statics

Figure 1 facilitates some simple comparative static exercises. Consider each of the boundary conditions in turn.

I. Leap Feasibility, $F = 0$:

If $\theta \underline{d}$ increases, then from condition $c(S_i^*) = p_{y_i} - \theta \underline{d}$, we can see that $c(S_i^*)$ decreases. This implies the value of S_i^* increases. The $F = 0$ curve shifts to the right.

If p_{y_i} increases, then from condition $c(S_i^*) = p_{y_i} - \theta\underline{d}$, we can see that $c(S_i^*)$ increases. This implies the value of S_i^* decreases. The $F = 0$ curve shifts to the left.

II. Leap Incentive, $I(S_i, S_k) = 0$:

If $\overline{c}$ increases, then from condition $c(S_k^*) = 2(p_{y_k} - \theta\underline{d}) - \overline{c}$ we can see that $c(S_k^*)$ decreases. This implies the value of S_k^* increases. This implies the $I(S_i, S_k) = 0$ curve shifts to the left.

If $\theta\underline{d}$ increases, then from condition $c(S_k^*) = 2(p_{y_k} - \theta\underline{d}) - \overline{c}$ we can see that $c(S_k^*)$ decreases. This implies the value of S_k^* increases. This implies the $I(S_i, S_k) = 0$ curve shifts to the left.

Note that if $\theta\underline{d}$ increases, both curves shift. The $F = 0$ curve moves right and the $I(S_i, S_k) = 0$ moves left, reducing the shaded area where both constraints are favorable to growth acceleration.

These results also provide straightforward implications for the location of a country's RCA set in product space, which we state in the form of a Proposition.

Proposition 1

(A) If the country RCA set is situated in a sparse part of the product space, then the fixed cost of leaping to a new product, $\theta\underline{d}$, will be high, resulting in a smaller shaded area. This implies a lower likelihood of growth acceleration.

(B) If the country RCA is situated in a dense part of the product space, then both current and potential spillovers, S_i and S_k respectively will be high, lying in the shaded area. This implies a higher likelihood of growth acceleration.

Together the conditions embody the importance of network spillovers and distance to potential products. Our empirical investigation attempts to identify the economic and statistical significance of these factors.

4 Empirical Strategy

Following the outline in the introduction, there are several steps to our empirical strategy. We describe these in more detail below.

4.1 The Transformation of Product Space

The first step in our empirical methodology is to examine if the product space network has evolved over time, and how it intersected with country-level specialization, in order to see if there is evidence for our hypothesis that for some countries the overlap between the two created conditions increasing the likelihood of a growth acceleration. To this end we first map the product space between 1962 and 2000. As described earlier, we can consider product space to be a complex network, where each product represents a node in the network and the proximities between products are used to denote weighted links between them. Given the symmetry of the proximity matrix, the resulting network can be characterized as an undirected network. With this representation, we study the evolution of product space via properties of the network[5].

A simple way to see that product space has changed over time is to look at the correlation of the proximity matrix between products through time. We therefore compute the Pearson correlation coefficient for the proximities between each pair of products across time. The correlations for five-year intervals (except for 1962-65) are shown in Table 1. We see that the product space was fairly stable between 1962 and 1970, with the correlation between these years being 0.90. From the 1970's however, the pace of change picks up, and product space seems to change substantially over each decade, with the changes becoming more significant as the separation exceeds fifteen years. All the correlations between product space matrices more than fifteen years apart are below 0.50, except for the 1965 to 1980 period where the correlation coefficient is 0.68.

[Table 1]

While the correlation matrix gives us the sense that product space has changed quite significantly over the last forty years, we would like to know more about the nature of these changes. How has the connectedness of product space changed between 1965 and 2000? Are sectors that are tightly connected in 2000 the same sectors that were tightly connected in 1965, or are there big differences in the sectors of product space that are strongly connected? If the topology of product space has indeed changed considerably, can we identify which industries have declined and which have risen in terms of network connectivity?

To answer these questions we draw upon methods developed recently in the physics literature to detect *community structure* in networks, meaning the existence of some natural division of the network such that nodes

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[5] While there are many properties of the network that can be studied and might be interesting in their own right, such as network density and distribution of links, since we are primarily interested in properties that relate to our conjecture we focus here on the correlation between the matrix over time and community structure of the network.

within a group/sub-network are highly associated among themselves, while having relatively fewer/weaker connections with the rest of the network. Because communities are relatively independent of one another structurally, the detection of such groups could be of significant practical importance. For example, a community in genetic networks contains genes with similar functions, and a community in the World Wide Web may correspond to web pages related to similar topics. In our context, a community of nodes signifies products likely to be exported together, due to technological and knowledge complimentarity between them.

The partitioning of a network into communities can be done in two different ways. One way is to use a community structure algorithm that decides by itself the most appropriate community structure without prior knowledge about the network, and is able to distinguish between networks having clear community structures and networks with essentially random structures. This approach organizes the data into communities based solely on the data, that is there are no assumptions made regarding the specific members for each cluster or the number of clusters that are being identified[6]. We use this approach to focus on the first two questions posed above, relating to the transformation of product space as a whole.

Another way to is to use knowledge about the number and allocation of nodes into communities that are relevant for the study. In the case of the product space we want to focus the analysis on the specific dynamics within and between industries within the product space and therefore use SITC codes to define the community structure. This is called *graph partitioning.* We use this approach to focus on the third question posed above, relating to the rise and decline of specific industries over time in terms of network connectedness.

The community structure algorithm for networks that we use here was proposed by Ruan and Zhang (2008) and it is referred to as QCUT. This methodology is a refinement (and extension) of the algorithm proposed by Newman (2007). We use the QCUT algorithm to identify the communities into which the product space is partitioned in the year 2000 and then we use this community structure to partition the product space of other years into communities. This allows for the visual inspection of changes inthe product space. Figure 2 presents the hierarchical clustering for the year 2000, where the proximities between each product in the product space are presented in a color coded matrix (black = no interaction and white = high proximities). Figure 2 also shows the results for the product spaces of 1970, 1980, and 1990

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[6] This method is also referred to as hierarchical clustering.

when these are partitioned according to the community structure defined by the QCUT algorithm for the product space in 2000. Clearly the community structure of 2000 is not a good representation of the state of connectedness of the product space for 1990, 1980, and 1970. In 2000, the interaction within community D and between this community and others in the product space is very low, as judged by the lack of grey-white pixels in these areas, while in 1970 the interaction of products within community D and between this community and products in other communities was relatively high.

[Figure 2 here]

In order to quantify the degree of change that the product space has experienced over time using a well defined metric, we use the Jaccard Index also known as the Jaccard similarity coefficient (Jaccard, 1901; Tan, Steinbach and Kumar, 2005), a statistic used for comparing the similarity and diversity of sample sets.. The Jaccard index measures similarity between sample sets, and is defined as the size of the intersection divided by the size of the union of the sample sets. For our context, assume a benchmark community structure C_1 and an alternative one referred to as C_2, and let S_1 be the set of vertex pairs in the same community in C_1, and S_2 the set of vertex pairs in the same community in C_2. Then the Jaccard Index, which lies between 0 and 1, is,

$$J(S_1, S_2) = \frac{|S_1 \bigcap S_2|}{|S_1 \bigcup S_2|} \tag{6}$$

For the benchmark community we use here, as in the community structure examination, that for the product space of 2000. We then compare the community structures of all the other years against this benchmark. The results, in Figure 3, (*Javier, could you draw a line connecting the points?*) also suggest substantial changes in the product space through time. There also seems to be evidence for a structural break in the rate of change in product space around 1980. There is a big difference between 2000 and 1980, but not much difference between 1980 and 1962.

[Figure 3 here]

While the visual representation of the changes of the product space through time, by examining community structure, and the results of the Jaccard Index suggest transformation in the product space over time, it does not enable us to identify where the transformations are taking place at an industry level. In order to study industry changes in connectedness we next compare specific product space network partitions, where the "communities" are pre-specified according to SITC one-digit industry codes. This partitions the product space into 10 SITC based clusters. The resulting 10X10 color coded graph partitioning of product space matrices for 1965, 1970, 1985 and 1995 is presented in Figure 4. We can see that the number of high intensity links (gray and white pixels) increases through time and is substantially higher in 2000 compared to 1965. The elements of this matrix on the diagonal denote the sum of the proximities that exist within industries, relative to the overall sum of proximities for the whole matrix, while the off diagonal elements report the sum of proximities that exist between industries, relative to the overall sum *(are you saying the same thing twice? A bit confusing here). Some interpretation/intuition?.*

[Figure 4 here]

The color coded information matrices for 1965, 1975, 1985 and 1995 presented in Figure 4, provide an overview of the evolution of the product space at the industry level. In 1975 it is clear that the within-industry interaction of the manufactured goods (*classified by materials?*) industry (SITC 6/*should this be 7*) dominated the product space and there was a small degree of interaction between this industry and the machinery and transportation industry (SITC 7/*should this be 6?*). The SITC 6 classification includes iron, steel, and rubber, leather, paper and wood manufactures, while SITC 7 includes industrial machinery, data processing equipment, road vehicles, and telecommunications. Linkages within or between other industries are very scarce in 1970. Over time a bigger cluster forms around the manufactured goods (classified by materials) industry (SITC 6) that besides the machinery and transportantion industry (SITC 7) includes the industries of chemicals and related products (SITC 5) and the industry of miscellaneous manufctures (SITC 8). The SITC 5 industry classification includes goods like organic and inorganic chemicals, pharmaceutical products, fertilizers, and artificial resins, while SITC 8 includes more commercial manufactures like furniture, apparel, footwear, watches and photographic equipment. (*javier: based on the diagram it looks like what you're calling 6 should be 7, or am I confused?*)

To sum up, the results presented here suggest that the product space of relatedness has not been static over the past 35 years. The number and the likelihood of pairs of products being exported together have increased. In terms of how the product space has changed, we see that specifically the manufacturing industries (SITC 6 and SITC 8) and their overlaps with chemicals and related products as well as with machinery and transportation equipment industry have been the sectors that have experienced the clearest transformations in terms of becoming more tightly connected to surrounding industries.

4.2 Country Level Specialization and the Small World

We now move from "global" product space to "local" country-level patterns of product specialization. Here we superimpose country-level patterns of product specialization on product space to see if there is evidence consistent with our small-world hypothesis. If a country's product specialization lies in industries that are in the tightly connected regions of product space then it is better positioned to take advantage of spillover effects within those industries and also across industries which overlap with the connected cluster. Such a topology could come about because either or both product space and the country-level patterns of product specialization have changed over time so as to intersect in such a way as to create a "small world" and enable spillovers, investment and leaps that link to new products.

The country-level pattern of product specialization, defined as the set of products for which the country has RCA (>1), can be superimposed on the product space. In other words, once the set of products for which a country has RCA in a given year is identified, these products and the proximities between them, as dictated by the product space, can be analyzed as an undirected complex network, just as was done for the product space. In addition, by using the graph partitioning process based on the one-digit SITC Industry codes described above, we can compare the evolution of product space and the country-level product specialization in a given period. We perform this exercise for three countries, Ireland, Korea and Greence. Ireland and Korea experienced an episode of growth acceleration, Greece did not.

First consider Ireland. The left hand panels of Figure 5 present the community structure of product space (top left panel) and the graph partitioning of product space (bottom left panel) in 1980, with one-digit SITC Industry code labels added to both panels. The right hand panels present community structure in Ireland's pattern of product specialization, (top right panel) and graph partitioning of its product specialization (bottom right panel). Figure 6 present the same information for Ireland in 1990. We know that Ireland experienced a growth acceleration episode in 1985, and from these two figures we can examine Ireland's country-level product specialization before and after the growth acceleration period. It turns out that Ireland's country-level product specialization pattern was highly correlated with the product space in 1980, and still is in 1990. The pairwise correlation between the specialization pattern for Ireland and the product space is above 0.80 in both years. It is worth noting that there is a clear increase in the *intensity of links* within industries SITC 5, SITC 6, SITC 7, and SITC 8 and their overlap with the food and live animals industry (SITC 0) which includes products like vegetables, fruits, meat, dairy products and other edible products, and the crude materials industry (SITC 2) which contains products considered as inputs in production like crude rubber, wood, textile fibers, pulp and waste paper. For Ireland, we can say that the high density portion of it's specialization pattern in 1980 was right on top of the highly clustered area of the product space. According to our hypothesis, this allowed Ireland to leap into inputs related products (SITC 0 and SITC 2) and expand its export product base.

[**Figures 5 and 6 here**]

Our second growth acceleration country is Korea and we present similar analyses in Figures 7 and 8. Korea experienced growth acceleration in 1984, so we replicate the analysis for 1980 and 1990. The graph partitioning diagram for 1980 shows that Korea's country-level product specialization lay on top of of the tightly connected part of the product space in 1980. In this case the pair wise correlation is close to 0.80, for both years, as it was for Ireland. But in contrast to Ireland's experience, Korea did not increase the interaction of manufacture oriented industries with other products (like input products in Ireland's case) in the period from 1980 to 1990. What happened in Korea is that the density of links and proximities (strength of links) within the SITC 7 products increased dramatically, and the interaction of products within this industry level and those in the SITC 6 and SITC 8 classifications expanded. These spillovers allowed Korea to expand its export basket in products like data processing equipment, telecommunications, sound recording equipment, electric machinery, road vehicles, and transportation equipment, and this also benefited exports of products like apparel, footwear, and furniture (all SITC 8) and manufactured leather, rubber, non-metallic products (all SITC 6).

[**Figures 7 and 8 here**]

We now look at the country-level product specialization of Greece, a country that did not experience growth acceleration and therefore can be used as a counter example to the cases of Ireland and Korea. We replicate the analysis presented above, using the same years, 1980 and 1990, in order to provide some consistency across the comparisons. From Figures 9 and 10 we can see that although Greece's country-level product specialization in 1980 has a relatively high level of interaction within the manufacturing industry (SITC 6), there is no interaction between this industry and the other high density industries (SITC 5, SITC 7, and SITC8). In fact, the manufacturing industry in Greece has its biggest overlap with the SITC 0 industry, similar to Ireland's case, but the overall pair-wise correlation of Greece's country-level product specialization with the product space is 0.66, which is lower than that of Ireland or Korea. When we compare the results of 1980 with those of 1990, in Figures 9 and 10, we can see that Greece's specialization pattern shows no major transformation, across the board or within/between industries' degrees of interaction *and correlation with product space even falls slightly from 0.67 in 1980 to 0.58 in 1990.* This suggests that the spillover effects that were present in Ireland's and Korea's case were arguably absent in Greece's case.

[**Figures 9 and 10 here**]

In summary, we see that the country-level product specialization of some countries has changed over time, like Ireland and Korea, but there are also cases wher we observe no meaningful changes, like Greece.

4.3 Network measures of spillovers and distance

In order to empirically test the small world hypothesis, we need to examine if a country's pattern of product specialization prior to growth acceleration (GA) resembles a small world in the product space network. To this end, we consider a country's pattern of product specialization five years prior to the start of the GA episode and calculate network measures that we believe capture product spillovers and distance in product space. We describe our network measures below.

Product Distance

First, we measure the average proximity of a new potential product j (that is not in the current export basket of country k) to a country's current productive structure, which Hidalgo et. al (2007) first proposed, and called "density."

$$\omega_j^k = \frac{\sum_i x_i \phi_{ij}}{\sum_i \phi_{ij}} \tag{7}$$

where ω_j^k is the density around good j given the export basket of the kth country and $x_i = 1$ if $\text{RCA}_{ki} > 1$ and 0 otherwise. Note that a high density value means the kth country has many products in its product specialization basket linked to the jth product.

Second, we find the average of ω_j^k over all the potential products $j = 1, ...m$, that are not in the export basket of country k, $D_k = \frac{1}{m} \sum\limits_j \omega_j^k$.

D_k is a measure of how well connected country j's pattern of product specialization is to the rest of product space, and can thus be interpreted as a measure of how 'close' country j is to the set of potential products. Note that a higher value of D_k corresponds to greater closeness/shorter distance in product space. In our econometric analysis we label this measure closeness.

Product Spillovers

In accordance with our theoretical framework, we compute two separate measures of country-level product spillovers: current spillovers – spillovers within its pattern of product specialization, and potential spillovers – spillovers to products outside its current pattern of product specialization.

(a) **Current Spillovers**: For this measure we take the density measure described in (7) and make two modifications to it. In the denominator, we only consider the set of products (i) in a country's export basket and compute the sum of proximities from every other product in product space to product i. In the numerator, we consider only the proximities from the products leading to that particular product (i) from the products that are also part of the country's export basket. This can be interpreted as the density of links for a product i that is part of a country's export basket that only come from within the set of export basket products. We then weight the "within" product density measures thus constructed for all of the products in a country's export basket by their export shares to come up with one number for each country. This gives us a measure which captures spillovers within the products that constitute a country's export basket.

(b) **Potential Spillovers**: For this we compute a measure of the network centrality of a country's export basket. First, we compute the centrality for each product in a country's export basket to every other product in the product space. Product i's centrality is the average of its proximity to every other product,

$$centrality_i = \frac{\sum\limits_j \phi_{ij}}{J} \tag{8}$$

A product that is more central in the product space will be connected to a greater proportion of the J products and will therefore have a higher value for centrality. Then we create a weighted average of product centrality for a country k where the weight is the export share of each product,

$$Centrality_k = \sum_{i \in k} \left(\frac{e_i}{\sum\limits_{l} e_l} c_i \right) \tag{9}$$

where e_i represents the export value of product i and l indexes all the products in country k's export basket. Finally we scale country centrality by the number of products in a country's export basket to yield $n_k C_k$. Scaling by the number of products captures economies of scale and scope effects. This gives us a measure that captures the position of a country's export basket in overall product space, leading to potential spillovers into new products.

4.4 In the right space at the right time?

Since our hypothesis is that there is something special about the pattern of product specialization of the countries which experienced growth acceleration in relation to product space, we will aim to examine if, prior to the growth acceleration episode, these measures were different between the set of countries which experienced growth acceleration (GA countries) and a set of comparable "control group" (CG countries), in a statistically and economically significant sense. Then we plan to use these measures of spillovers and distance in a multivariate regression exercise (with suitable control variables) to see the extent to which they are capable of explaining the likelihood of growth acceleration.

5 Results

We have computed the network measures described above and run probit regressions to see if these variables are able to predict the probability of a growth acceleration. The variables appear to be both statistically and economically significant in all of the specifications we run. We are currently in the process of writing up our empirical results with suitable tables. We will present these results in full at the conference.

6 Broader Implications: The Architecture of Growth

We believe that a network approach along the lines described has the potential to uncover "structural" properties of product specialization, comparative advantage and their relationship to economic growth that have not been examined in the literature. If we find support for the hypothesis that there is a unifying pattern in the way in which the products that a country possesses comparative advantage are related (such as a small world topology), then we will have made important progress in decoding the mystery of growth acceleration. This in turn will lead to important implications for industrial and development policy. For example, it could suggest ways in which a country could target or prioritize sectors of the economy given its current pattern of product specialization so as to be well-primed for a development trajectory. At a more fundamental level, such evidence could lead to a re-evaluation of international trade and its relationship to economic development. The novel network approach can also prompt new empirical research directions by looking at trade relationships in a different way than conventional approaches.

The network-based methodology can unravel characteristics of the growth acceleration process that are difficult to both see and understand using conventional approaches. In this sense, the methodology itself can expand the scope of the questions that we will be able to ask. For example, as outlined earlier, the literature on complex networks proposes many ways in which the small world configuration may arise (short-cuts, hubs, modularity). This in turn suggests that a number of different policies and/or accidents could lead to this optimal configuration. A diversity of ways may lead to the possibility of growth acceleration. It is an understatement to say that policy implications of such findings could be useful for crafting development strategies and bring about a fundamental re-evaluation of current approaches.

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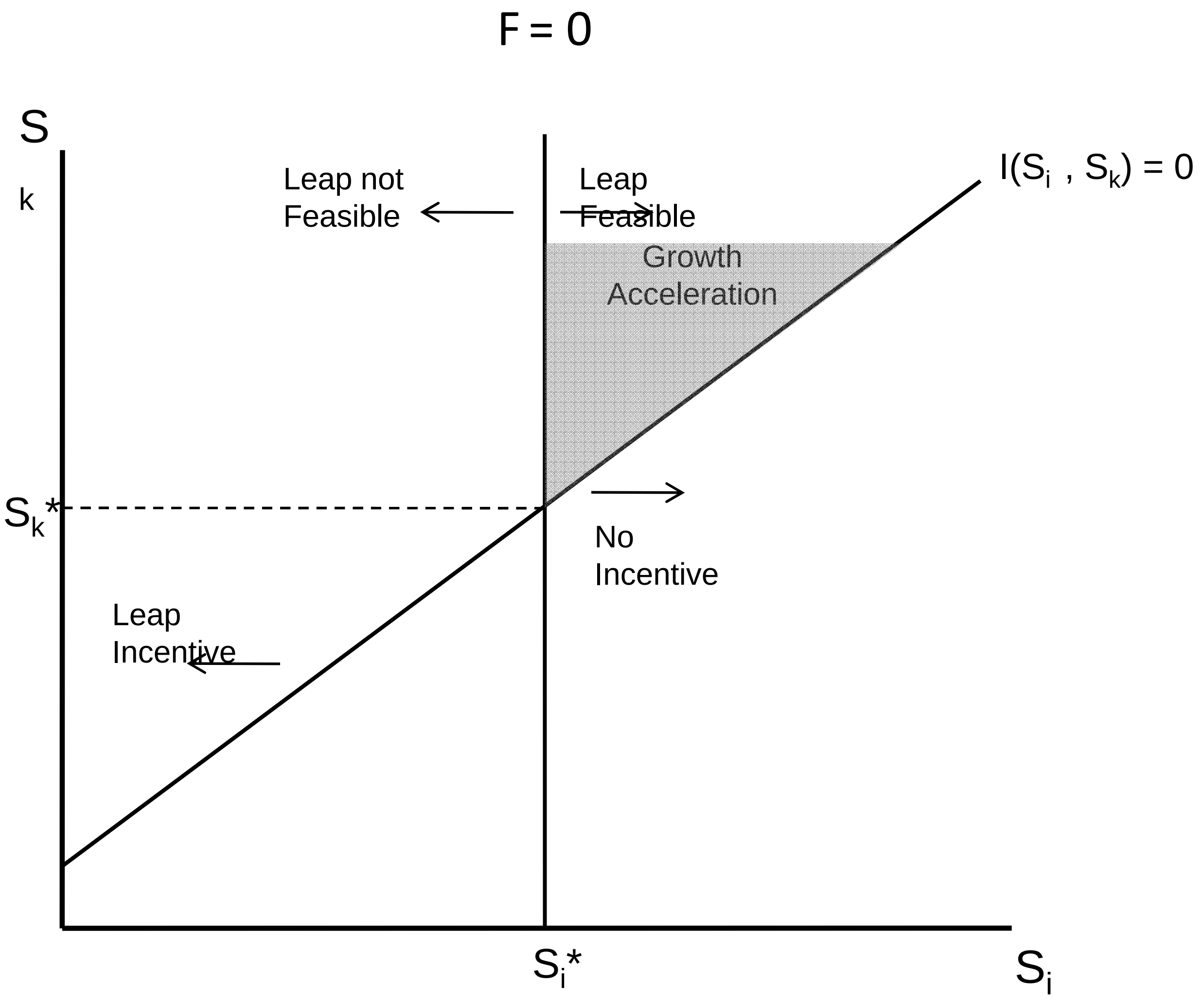

F = 0

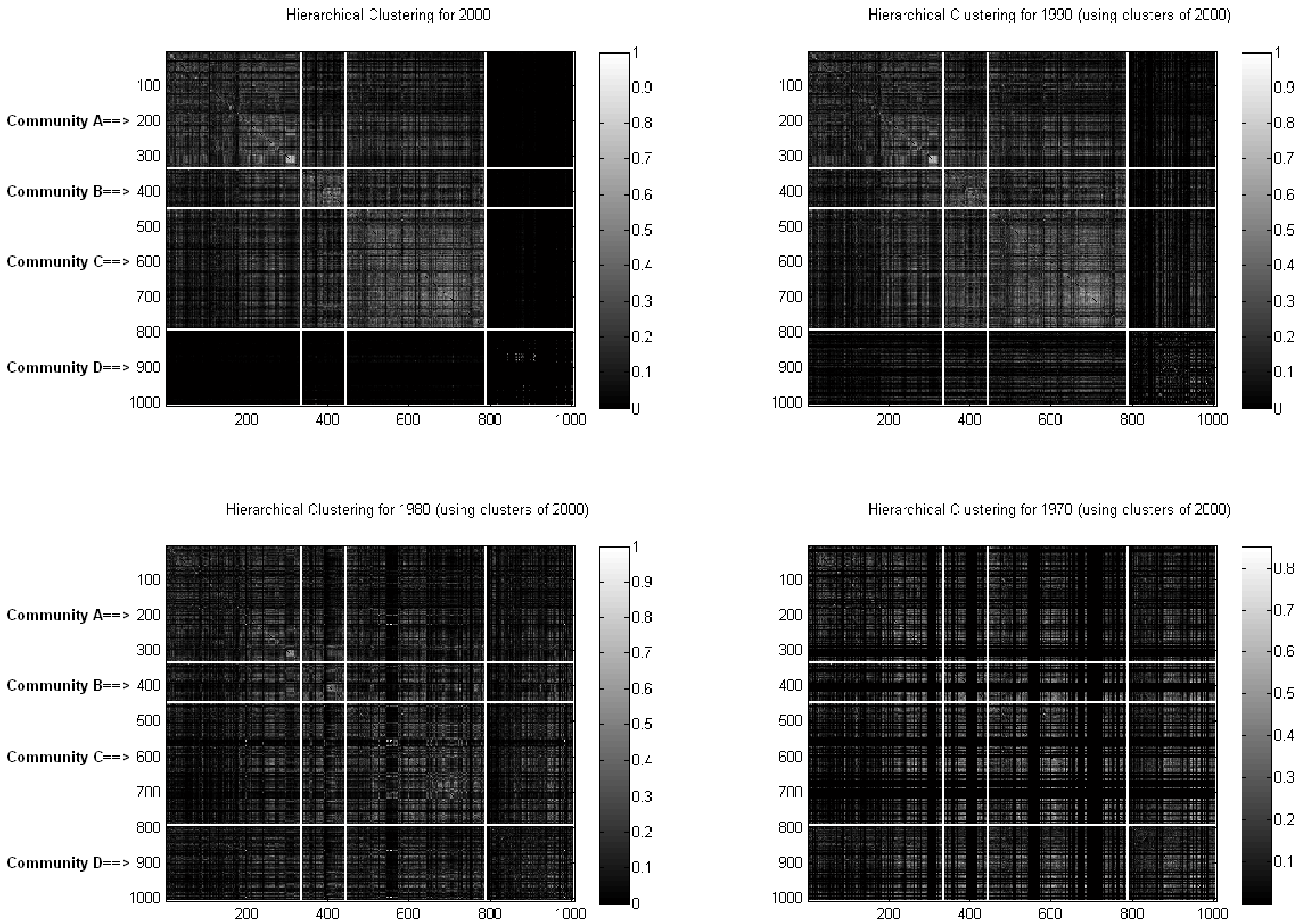
S_k
$I(S_i, S_k) = 0$
Leap not Feasible
Leap Feasible
Growth Acceleration
S_k*
No Incentive
Leap Incentive
S_i*
S_i

Figure 1

Correlation between Product Space Proximities across Time

	1962	1965	1970	1975	1980	1985	1990	1995	2000
1962	1								
1965	0.93	1							
1970	0.90	0.97	1						
1975	0.69	0.76	0.81	1					
1980	0.62	0.68	0.73	0.91	1				
1985	0.36	0.42	0.46	0.58	0.72	1			
1990	0.29	0.34	0.38	0.50	0.62	0.94	1		
1995	0.16	0.20	0.24	0.35	0.43	0.69	0.83	1	
2000	0.16	0.20	0.24	0.35	0.43	0.68	0.81	0.98	1

Table 1



Hierarchical Clustering for 2000

Hierarchical Clustering for 1990 (using clusters of 2000)

Hierarchical Clustering for 1980 (using clusters of 2000)

Hierarchical Clustering for 1970 (using clusters of 2000)

Figure 2

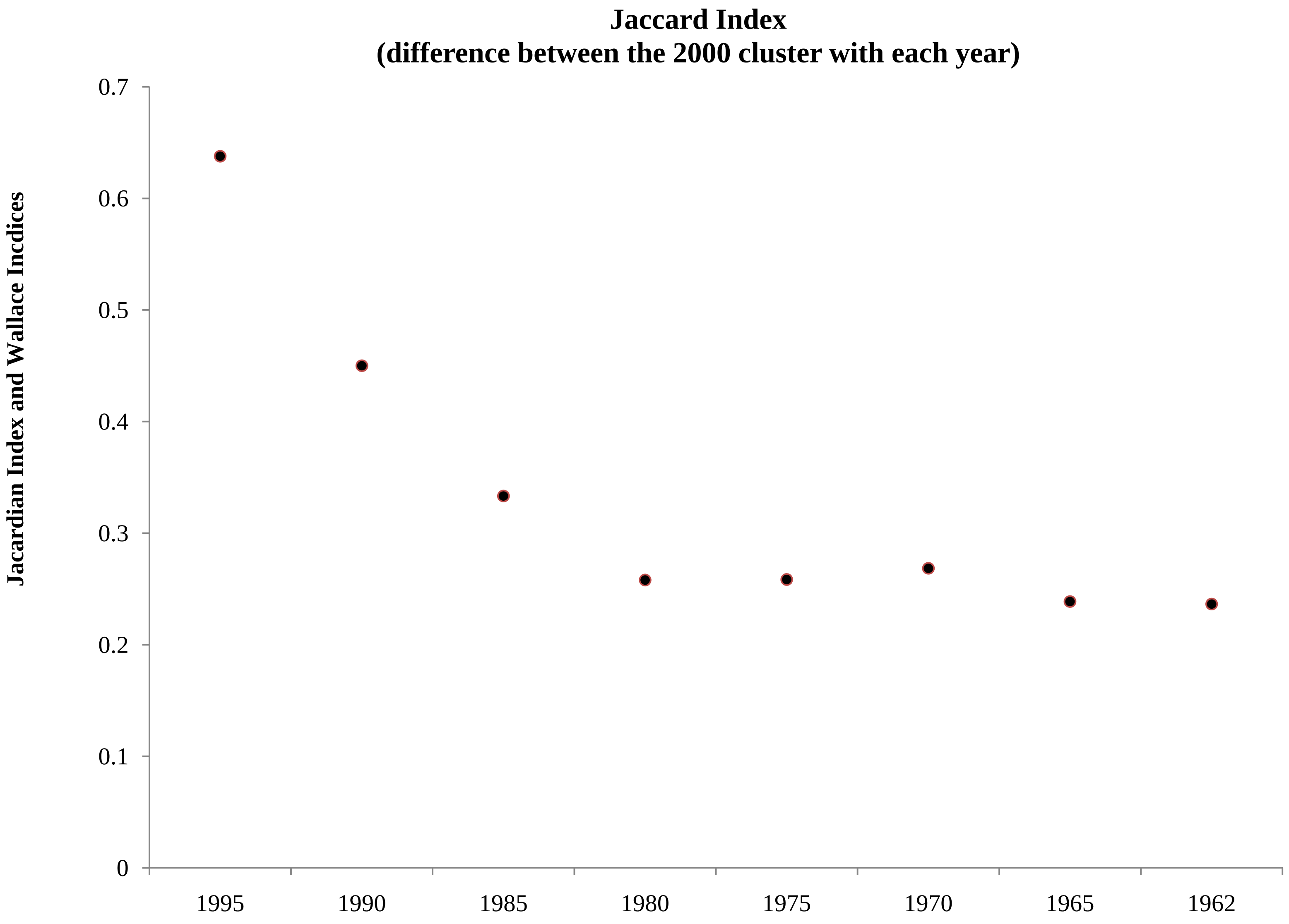

Jaccard Index
(difference between the 2000 cluster with each year)
Jacardian Index and Wallace Incdices
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1995
1990
1985
1980
1975
1970
1965
1962

Figure 3

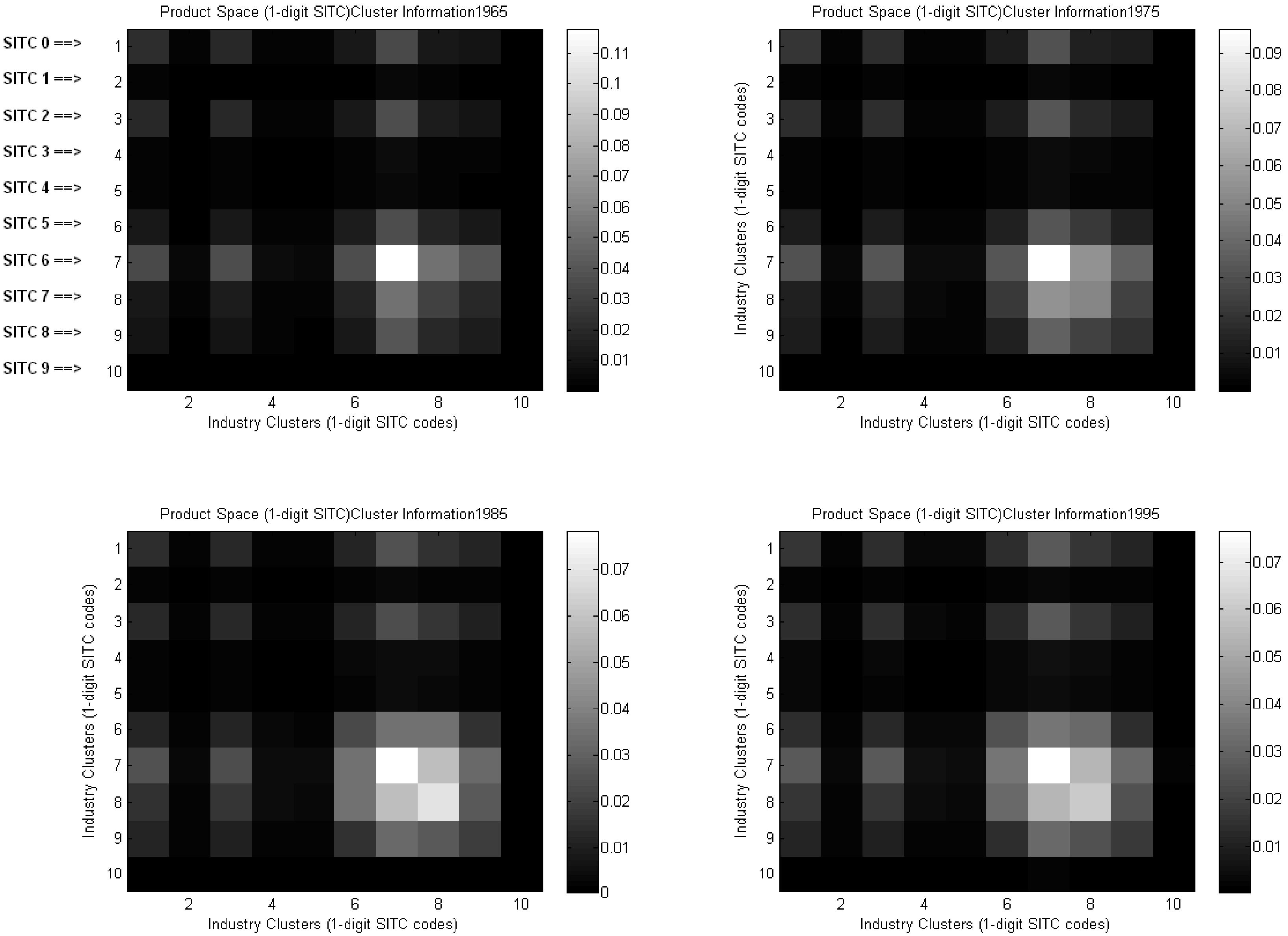
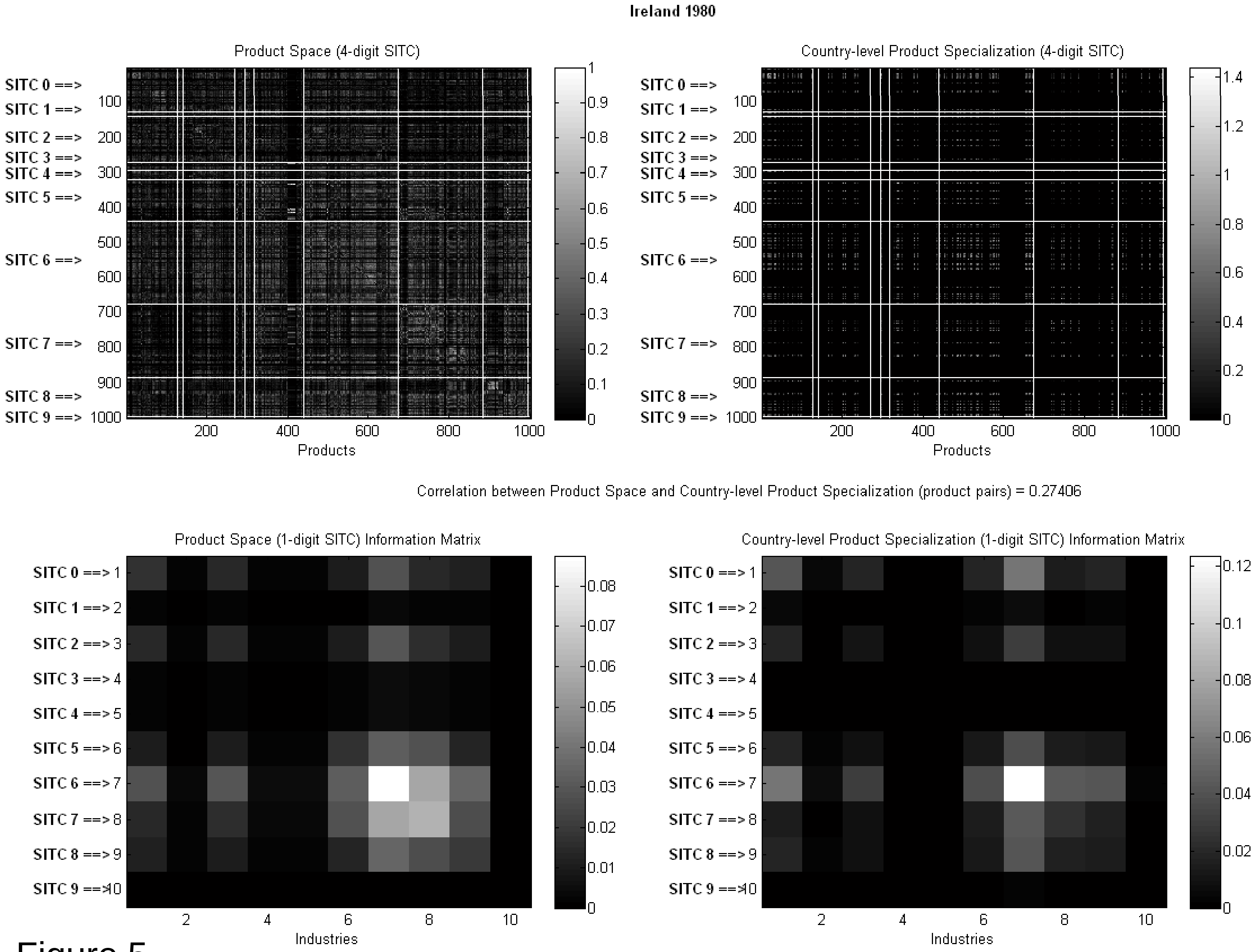

Product Space (1-digit SITC)Cluster Information1965
SITC 0 ==>
SITC 1 ==>
SITC 2 ==>
SITC 3 ==>
SITC 4 ==>
SITC 5 ==>
SITC 6 ==>
SITC 7 ==>
SITC 8 ==>
SITC 9 ==>
1
2
3
4
5
6
7
8
9
10
2
4
6
8
10
Industry Clusters (1-digit SITC codes)
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
Product Space (1-digit SITC)Cluster Information1975
Industry Clusters (1-digit SITC codes)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
Product Space (1-digit SITC)Cluster Information1985
Industry Clusters (1-digit SITC codes)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Product Space (1-digit SITC)Cluster Information1995
Industry Clusters (1-digit SITC codes)
0.07
0.06
0.05
0.04
0.03
0.02
0.01

Figure 4

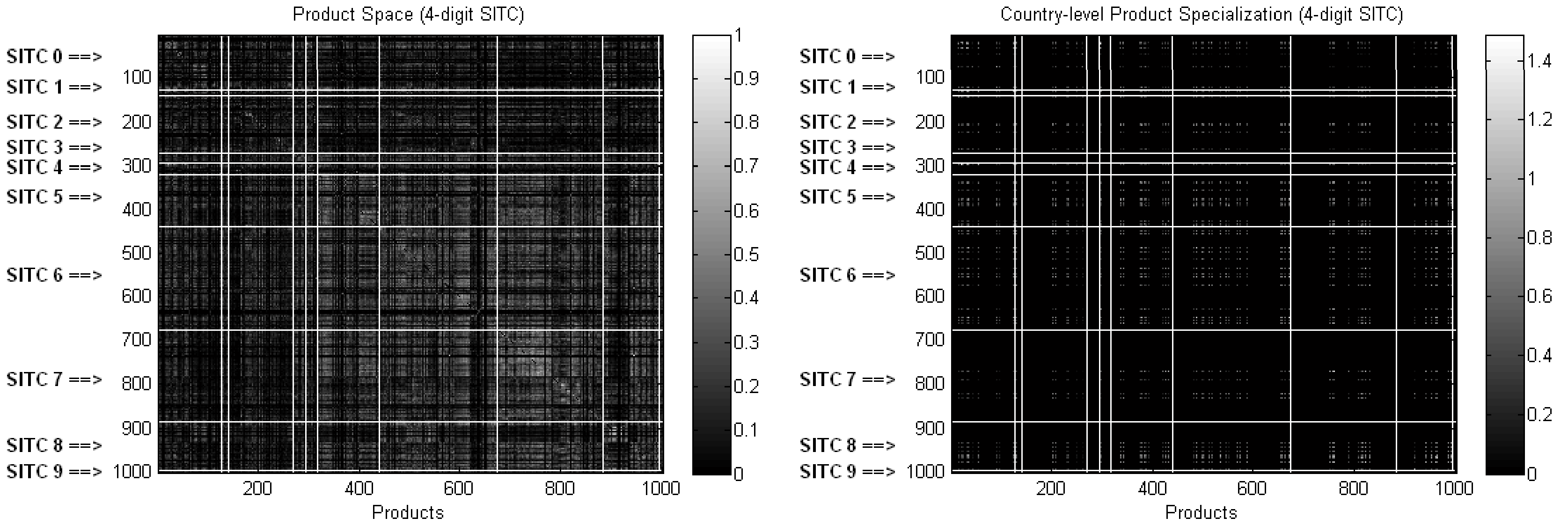


Correlation between Product Space and Country-level Product Specialization (product pairs) = 0.27406

Figure 5

Correlation between Product Space and Country-level Product Specialization (industry interactions) = 0.88815

Ireland 1990



Correlation between Product Space and Country-level Product Specialization (product pairs) = 0.21363

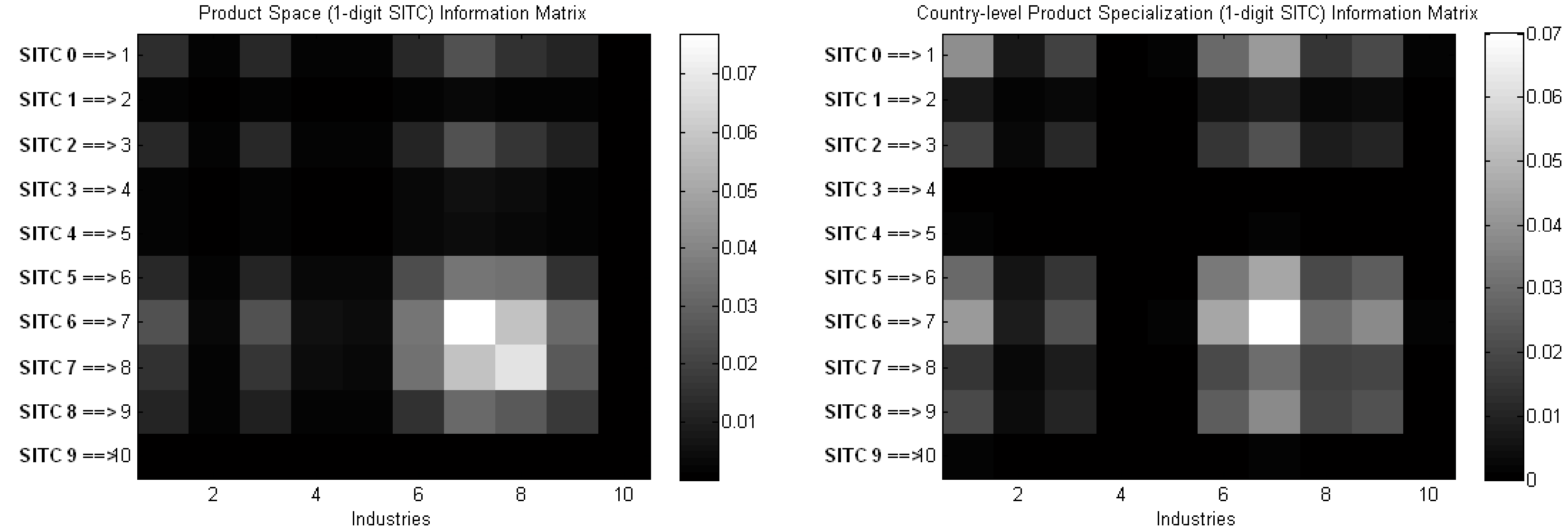
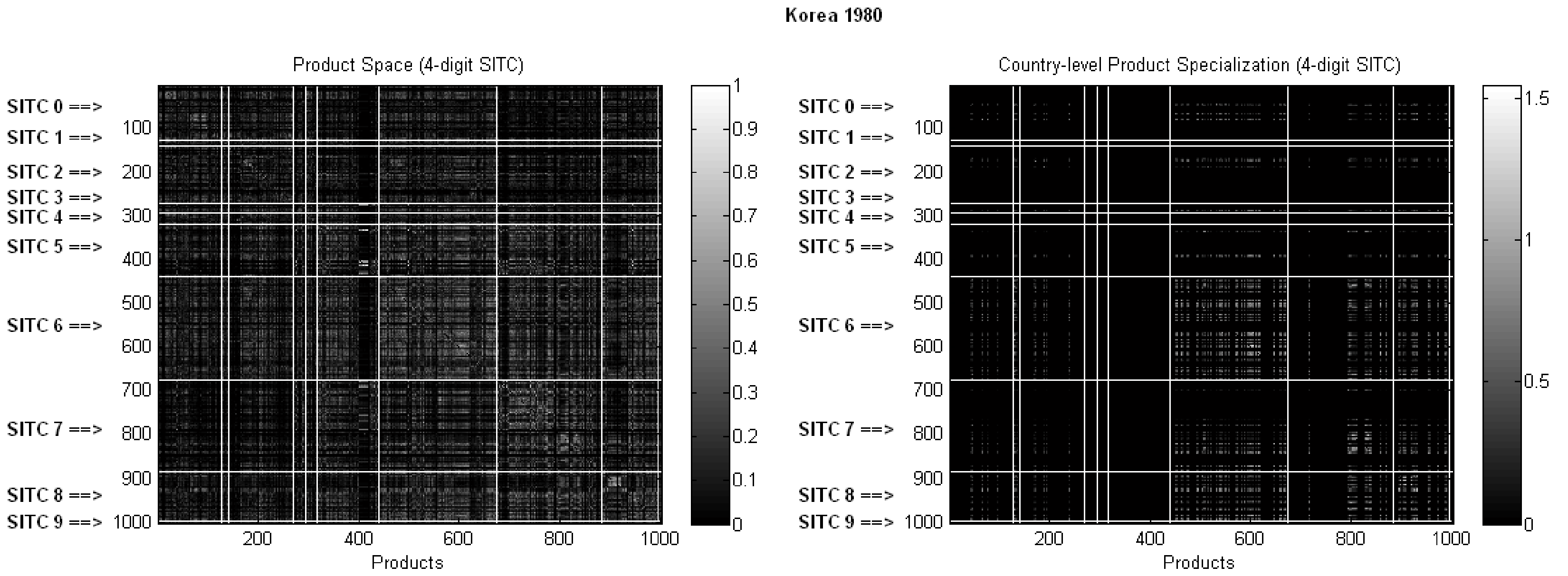
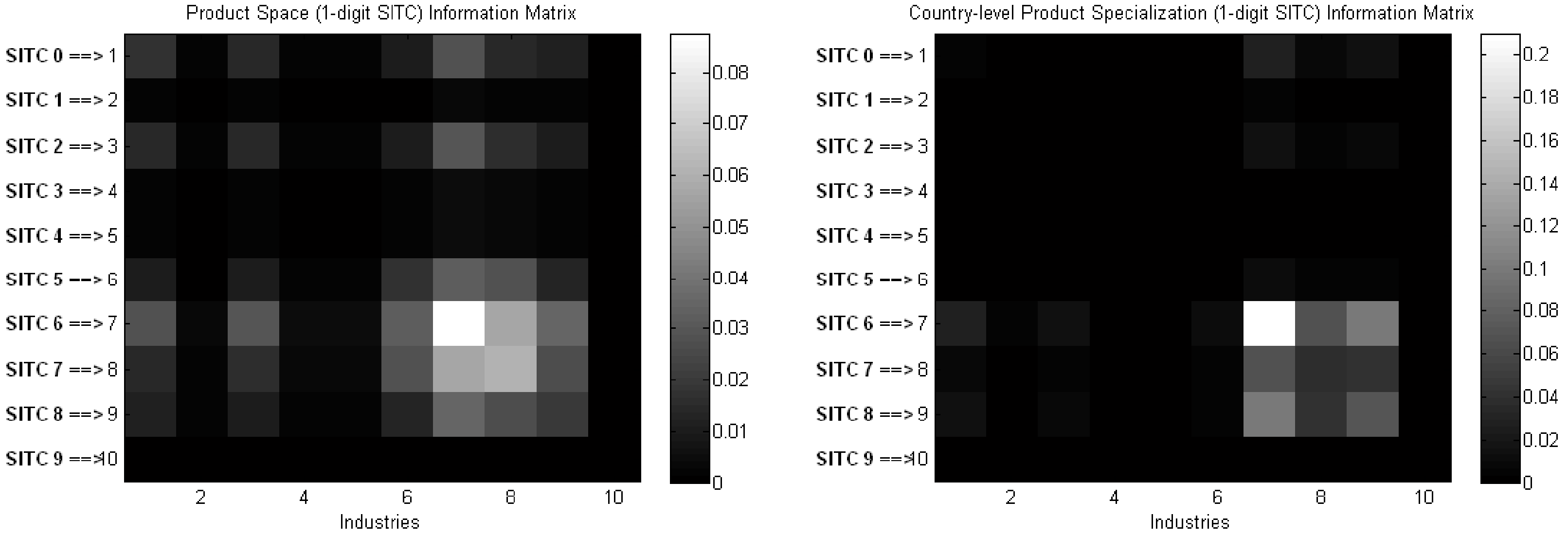


Figure 6

Correlation between Product Space and Country-level Product Specialization (industry interactions) = 0.82045

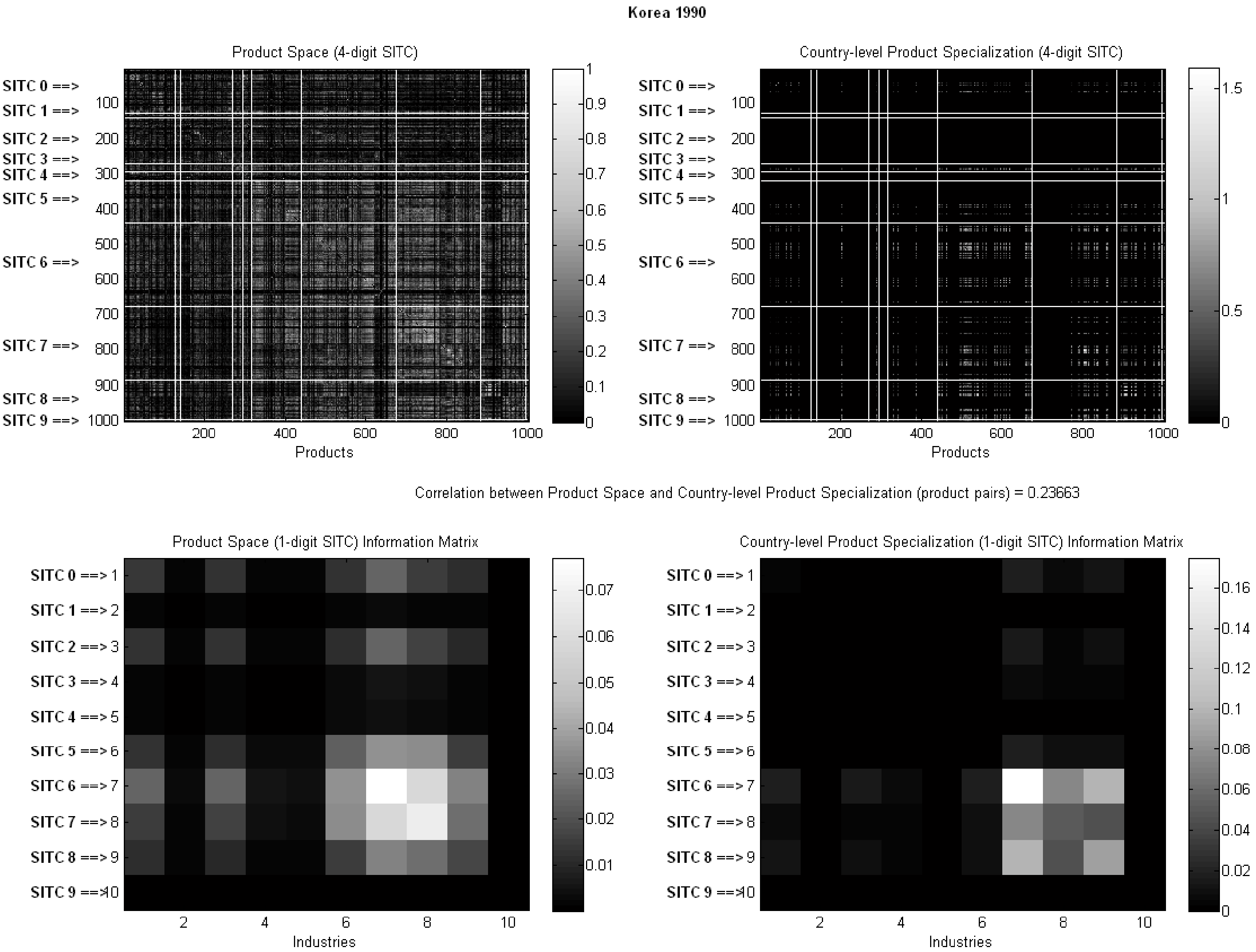

Korea 1980

Correlation between Product Space and Country-level Product Specialization (product pairs) = 0.27685



Correlation between Product Space and Country-level Product Specialization (industry interactions) = 0.81063

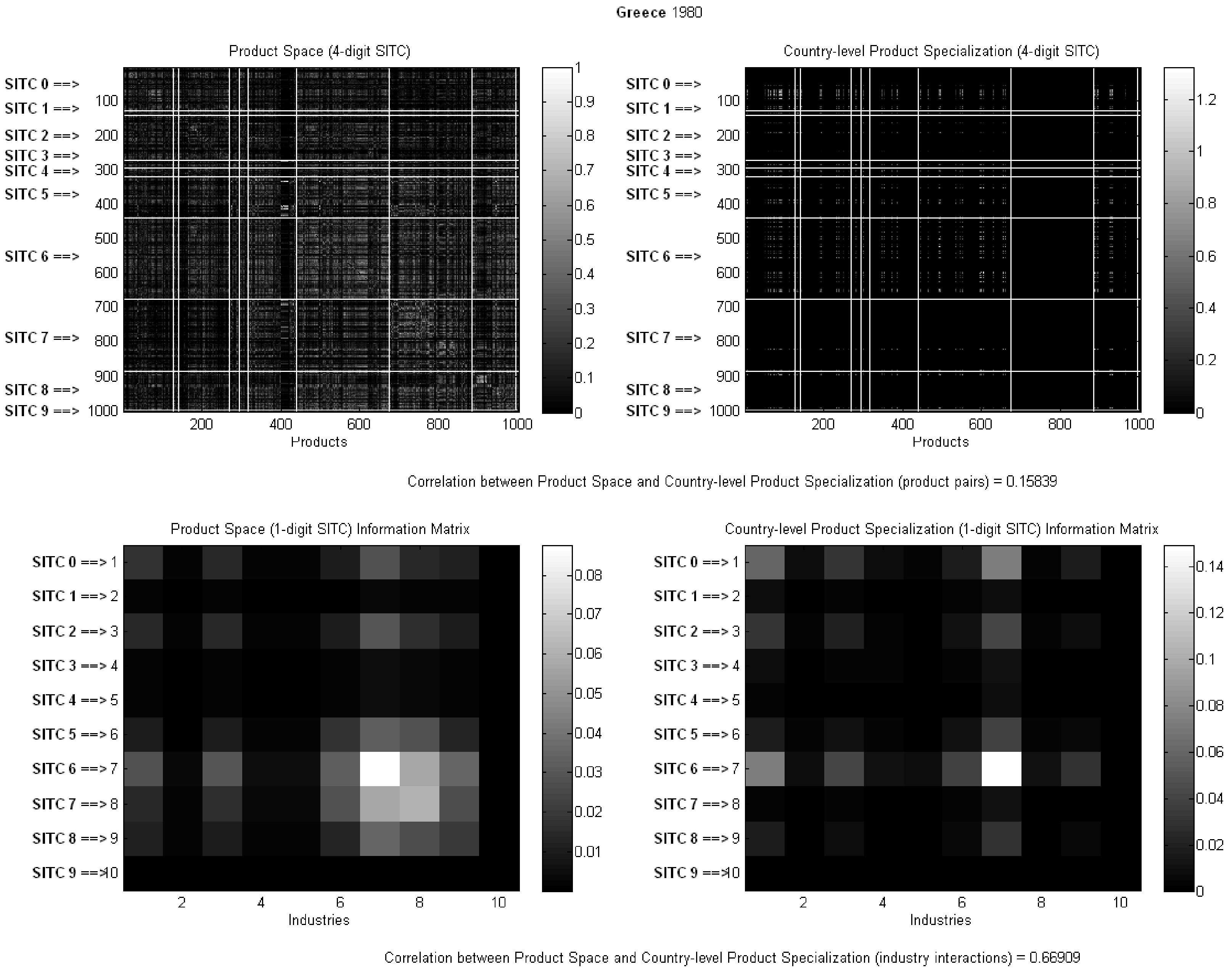
Figure 7



Correlation between Product Space and Country-level Product Specialization (product pairs) = 0.23663

Correlation between Product Space and Country-level Product Specialization (industry interactions) = 0.78028

Figure 8



Greece 1980

Product Space (4-digit SITC)

Country-level Product Specialization (4-digit SITC)

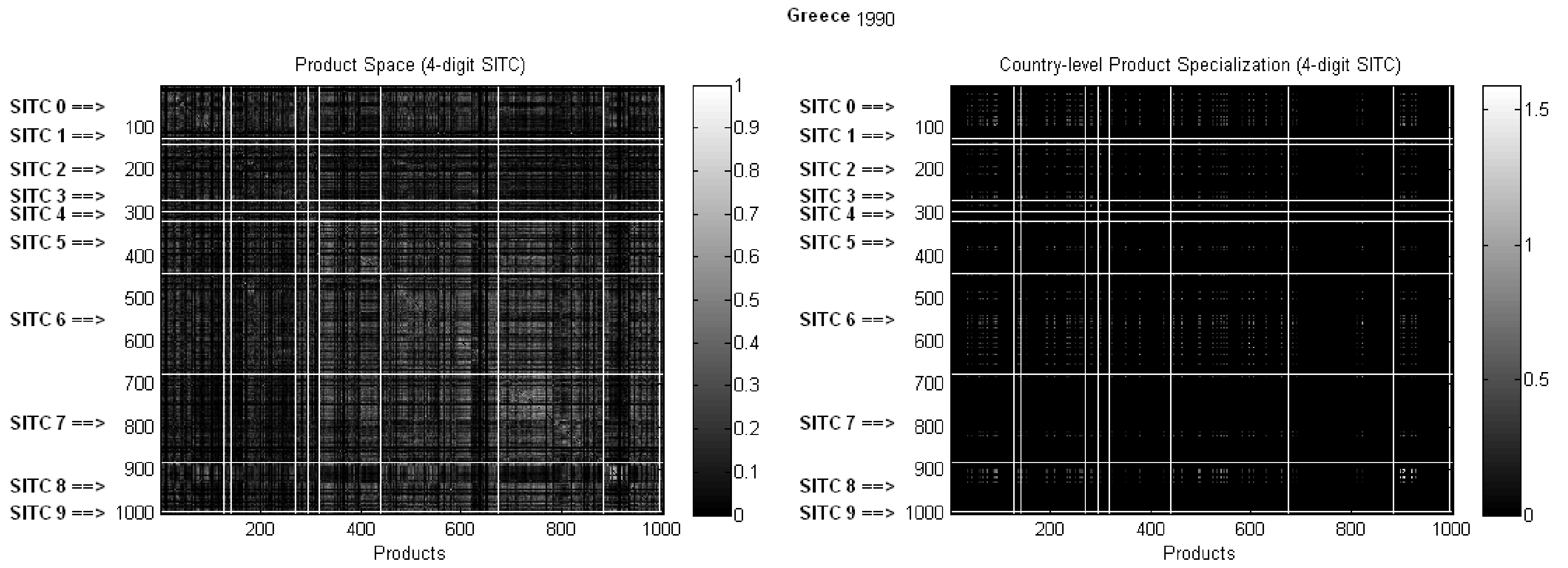
Correlation between Product Space and Country-level Product Specialization (product pairs) = 0.15839

Product Space (1-digit SITC) Information Matrix

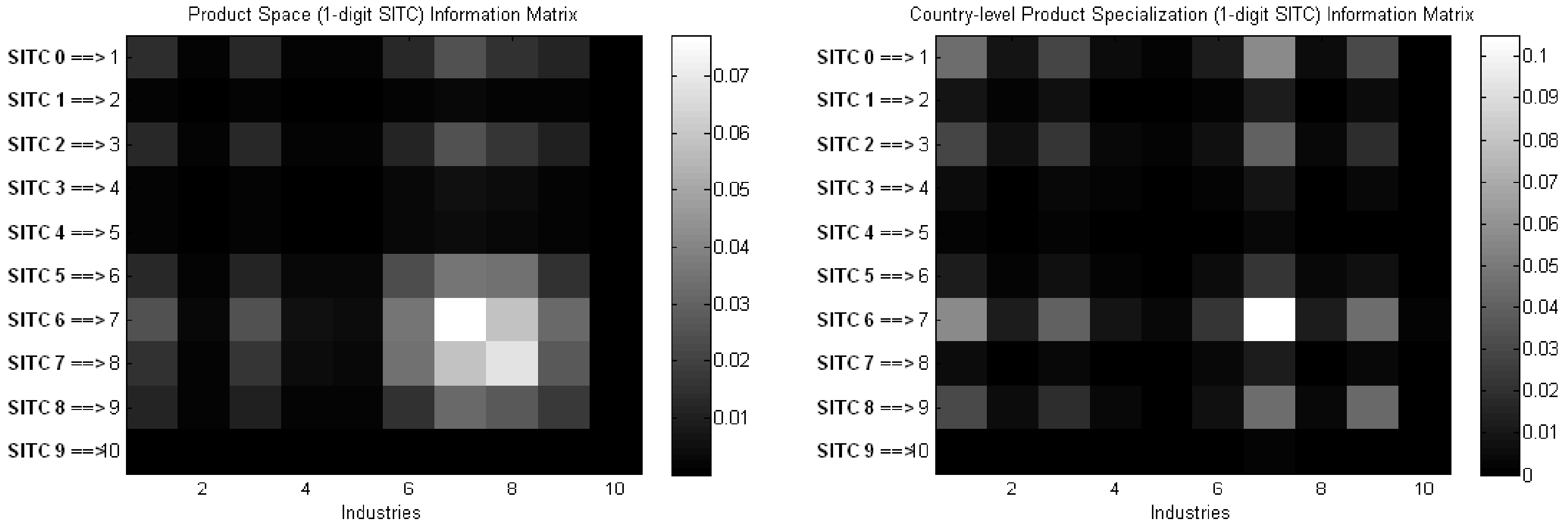
Country-level Product Specialization (1-digit SITC) Information Matrix

Correlation between Product Space and Country-level Product Specialization (industry interactions) = 0.66909

Figure 9



Correlation between Product Space and Country-level Product Specialization (product pairs) = 0.15375



Correlation between Product Space and Country-level Product Specialization (industry interactions) = 0.58453

Figure 10

SITC 1 digit

Code	Description
0	Food and live animals chiefly for food
1	Beverages and tobacco
2	Crude materials, inedible, except fuels
3	Mineral fuels, lubricants and related materials
4	Animal and vegetable oils, fats and waxes
5	Chemicals and related products, nes
6	Manufactured goods classified chiefly by materials
7	Machinery and transport equipment
8	Miscellaneous manufactured articles
9	Commodities and transactions not classified elsewhere in the SITC

SITC 2 digit

Code	Description
00	Live animals chiefly for food
01	Meat and preparations
02	Dairy products and birds' eggs
03	Fish, crustacean and molluscs, and preparations thereof
04	Cereals and cereal preparations
05	Vegetables and fruit
06	Sugar, sugar preparations and honey
07	Coffee, tea, cocoa, spices, and manufactures thereof
08	Feeding stuff for animals (not including unmilled cereals)
09	Miscellaneous edible products and preparations
11	Beverages
12	Tobacco and tobacco manufactures
21	Hides, skins and furskins, raw
22	Oil seeds and oleaginous fruit
23	Crude rubber (including synthetic and reclaimed)
24	Cork and wood
25	Pulp and waste paper
26	Textile fibres (not wool tops) and their wastes (not in yarn)
27	Crude fertilizer and crude minerals
28	Metalliferous ores and metal scrap
29	Crude animal and vegetable materials, nes
32	Coal, coke and briquettes
33	Petroleum, petroleum products and related materials
34	Gas, natural and manufactured
35	Electric current
41	Animal oils and fats
42	Fixed vegetable oils and fats
43	Animal and vegetable oils and fats, processed, and waxes
51	Organic chemicals
52	Inorganic chemicals
53	Dyeing, tanning and colouring materials
54	Medicinal and pharmaceutical products
55	Oils and perfume materials; toilet and cleansing preparations
56	Fertilizers, manufactured
57	Explosives and pyrotechnic products
58	Artificial resins and plastic materials, and cellulose esters etc
59	Chemical materials and products, nes
61	Leather, leather manufactures, nes, and dressed furskins
62	Rubber manufactures, nes
63	Cork and wood, cork manufactures
64	Paper, paperboard, and articles of pulp, of paper or of paperboard
65	Textile yarn, fabrics, made-up articles, nes, and related products
66	Non-metallic mineral manufactures, nes
67	Iron and steel
68	Non-ferrous metals
69	Manufactures of metals, nes
71	Power generating machinery and equipment
72	Machinery specialized for particular industries
73	Metalworking machinery
74	General industrial machinery and equipment, nes, and parts of, nes
75	Office machines and automatic data processing equipment
76	Telecommunications, sound recording and reproducing equipment
77	Electric machinery, apparatus and appliances, nes, and parts, nes
78	Road vehicles
79	Other transport equipment
81	Sanitary, plumbing, heating, lighting fixtures and fittings, nes
82	Furniture and parts thereof
83	Travel goods, handbags and similar containers
84	Articles of apparel and clothing accessories
85	Footwear
87	Professional, scientific, controlling instruments, apparatus, nes
88	Photographic equipment and supplies, optical goods; watches, etc
89	Miscellaneous manufactured articles, nes
91	Postal packages not classified according to kind
93	Special transactions, commodity not classified according to class
94	Animals, live, nes, (including zoo animals, pets, insects, etc)
95	Armoured fighting vehicles, war firearms, ammunition, parts, nes
96	Coin (other than gold coin), not being legal tender
97	Gold, non-monetary (excluding gold ores and concentrates)