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Essays on networks: Applications to diffusion, productivity and bargaining

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I. Introduction

Networks are ubiquitous in life. From friendships between co-workers and subway metro systems to the brain, all can be understood as a network. In the case of economics, the interdependency of economies can also be represented through a network. We define a network as a set of elements, which we refer to as nodes or vertices, and its relations which we call links or edges. Nodes can represent different things such as players, countries, firms, etc. Links represent the interactions, trade or other types of relationships between these.

The literature on the economics of networks (also known as network economics) has been steadily growing in the past few decades. Some of the pioneers in the field such as Jackson, Goyal and Wolinsky, focused mainly on small networks with formation and the properties for these to be stable à la Nash. Jackson and Wolinsky (1996) defined the "pairwise stability" condition for an undirected network to reach equilibrium in which there are neither incentives to continue forming links with other players or to break any existing ones. Bala and Goyal (2000) provided the corresponding conditions for the case of a directed network.

In this dissertation, we rely on tools from the fields of game theory, network science and graph theory to model and answer questions related to:

1. Ways to speed up the process of formation and expansion of a climate club in different regions of the world.
2. Finding productivity differences between groups of industries in Japan.
3. Infinite bargaining between players.

Each of these topics is addressed in a different chapter.

In recent times, the issue of developing and implementing climate policies to combat and restrict the effects of global warming has become an increasingly important subject for the economics profession. Economists and other social scientists working on these topics, developed different theories and tools to analyze ways in which countries can attain stable international climate agreements which allow for mitigation of CO2 emissions. Nordhaus (2015) proposes that countries form a climate club: a coalition of countries that agree to reduce emissions in a harmonized way, sanctioning non-members while providing club goods for those that decide to join.

In the second chapter of this work, we study how different countries in the European Union (EU) implemented climate policies and, by relying on tools from networks and game theory, we analyze how this process could have been sped up and which countries are key for this to occur. We relate this to the process of growth of a climate club: Countries that implement climate policies are or become members of the club while the rest of countries are considered to be outside of the club. We find that two countries acting as the initial club members, Germany and France, are sufficient for the club to grow faster compared to any other country in the EU.

In economics, networks have also found applications in macroeconomics to study topics such as economic shocks and growth. This approach brings many new tools and statistics that allows for types of analyses that were not possible before. Acemoglu et al. (2012) study the propagation of shocks throughout the economy by relying on input-output tables and geographic networks. By means of Cobb-Douglas preferences and production functions, these authors test and show that demand-side shocks spread upstream (to their input-suppliers) whereas supply-side shocks do it downstream (to their customers). They find that propagations of shocks through networks are larger quantitatively than the effects from direct shocks. Geographic networks are also shown to have large quantitative effects: The propagation of a shock to an industry at a local level has a higher impact on those that collocate with it.

In the third chapter, we also rely on input-output data, but instead of shocks, we study possible labor productivity differences across groups of industries in Japan. First, we observe that sigma and beta divergence patterns exist throughout industries in Japan from the beginning of the 1990s. Then, by using so called "community detection algorithms" developed in the field of network science, we partition the data for the period 1973-2012 from the Research Institute of Economy, Trade and Industry (RIETI) into clusters that have members that are tightly connected between themselves and weakly with those not belonging to the same cluster.

The above algorithm shows the presence of two network communities or groups: a collection of industries whose elements remain in the same group for the whole period under study (which we call a stationary community) and another group of industries that do not belong to the first one (which we refer to as a transitional community). We then proceed to reexamine the convergence pattern in Japan for each of the communities we obtained. From the results we observe that the divergence pattern is mostly given by the transitional community. Additionally, from the year 2007, convergence à la sigma reappears but only in the stationary community. On average, industries from the transitional community tend to have higher productivity than those from the stationary community.

The study of network formation seeks to explain how networks are created and why they take the form or shapes they have. We can separate network formation into two categories: Random network formation and strategic network formation. The former was initially developed in the fields of mathematics (graph theory) and information science, while the latter where developed mainly in computer science and economics.

In the fourth and final chapter, the position that players have in the network has the role of determining the payoffs they will obtain from the stationary game they are playing. We consider two different types of players in the game. Additionally, we consider connections between players of the same type to be cheaper than those with players of different type: players have a preference for players with similar background, culture or language. Prior to the bargaining stage, players form connections taking into consideration not only the trade-off between more outside options (given by additional connections to other players) and the costs of maintaining those additional links, but also what type of players they connect to. Finally, we characterize the sufficient conditions for all the possible pairwise stable structures: a) those in which no given pair of players desire to form new connections and b) no given player wishes to unilaterally break any existing one.

II. Expanding a Climate Club in Europe: A Network Simulation

Abstract

Coordinating and achieving international climate agreements is a pressing matter to combat climate change. We analyze the expansion of a climate club in Europe from 1996 to 2011. We simulate it as a virus disseminating through a network. For this, one of two alternative thresholds must be surpassed: One in terms of the relative frequency of interactions between countries of the same group or another in terms of the value of trade exchanges. We find that the second threshold fits in a more accurate way the actual sequence of events. Finally, we identify countries that, acting as seeds, accelerate the process of expanding the club throughout the network.

Keywords: Cascades, Climate clubs, Networks, Simulations, Targeting.

1. Introduction

Policies to fight global warming have in recent decades been gathering increasing interest from the economics profession and the wider public. A region of the world that has developed and implemented numerous climate change policies to a certain degree of success is the European Union (EU). The countries that conform it, whether they were original members or joined later, implemented these policies in tandem.

We are interested in studying how a climate club expands as different countries that trade with its members decide to join it. Additionally, we wish to understand if this process can be accelerated by considering the structure of the trade network in which the different trading partners participate. Had the original members of the club been others, which ones would have sped up the expansion of the climate club? This analysis could be useful in the design of incentives for joining a climate club.

Through a network model we simulate how European countries that were and would become members of the EU form and expand a climate club. These countries are connected with each other in the network through their trade flows. In the model, a country chooses whether becoming a member of the club through policy harmonization or not. We depict this as a virus spreading through a network with nodes changing color. To characterize the decision-making process, we rely on two alternative thresholds. The first one evaluates whether the number of neighbors of a target node, who are taking a given action (joining or not the club), is above a predefined value. The second one assesses if trading partners being members of the climate club are more important than those not being part of it, regarding the country's export destination. If the former have a higher weight than the latter, then the exporting country copies behavior and joins the club. In other words: the stronger the ties and volume of trade that a given country has with members of the club, the higher the incentives for it to also "switch" and join. By relying on a network we are able to model the interaction of various players simultaneously while analyzing the expansion of the climate club through various European countries.

We simulate our model by using both data of volumes of international trade and adoptions of climate change policies, for European countries, for the period 1996-2011. The numerical analysis simulates the waves in which countries joined the club. Our results suggest that the second threshold predicts these waves more accurately during the period we analyze. Depending on the parametric values, the threshold's ability to correctly predict each wave can go from 60 to over 70 percent. This is done by comparing the results of the simulations with the real data to see if there are any discrepancies.

Finally, we test which countries would allow for a faster expansion of the club and also determine the minimum number of countries that is sufficient for a cascade effect in our network to occur. We find that the most effective countries for the expansion of the club are Germany, France and Great Britain. Regarding the second goal, we encounter that as few as 1 to 2 countries (depending on the threshold value) are sufficient for the cascade to take place.

The rest of this article is organized as follows. Section 2 discusses the related literature. Section 3 describes the data used. Section 4 outlines the criteria to analyze the expansion of the climate club. Section 5 explains the results of the simulation. Section 6 concludes. [1)]

2. Related Literature

Different ways to abate and reduce emissions, such as International Environmental Agreements, have been proposed (Barrett 1994, Barrett 2005). These agreements work as coalitions in which environmental treaties between various trading partners are achieved, establishing conditions for trade and imposing sanctions in case these are not fulfilled. Another method consists of imposing an international harmonized carbon tax (Nordhaus 2006).

A newer approach is that of a "climate club" which works as a combination of the former two methods: A coalition of countries that agree to reduce emissions in a harmonized way. Countries that do not become members of the club or follow its rules once they join are sanctioned by an amount or in a way that offsets the incentives of keeping "business as usual" emissions of Greenhouse gases

(GHG).[2] In other words, their access to the markets of those belonging to the climate club or the benefits derived from it are cut or reduced (for example, in 2001 Greece was punished for not complying with EU environmental standards, quickly changing its attitude once it was told it would lose regional aid from the EU). This generates a stable coalition of countries that can, by combining environmental policies and trade sanctions, substantially reduce emissions (Nordhaus 2015). The harmonization works as a mechanism by which countries adopt similar policies (Holzinger and Knill 2005).

In a recent paper, Heal and Kunreuther (2017) explain that it is better to work with a small subset of countries to confront the issue of a global climate regime. If these countries implement certain types of policies to reduce GHG emissions, and if they are sufficiently influential, it can trigger a cascading effect that convinces others to imitate or follow suit.

Efforts by various parties to mitigate GHG emissions have not been efficient due to a lack of enforcement and insufficient participation (Barrett 2008). Furthermore, it is often the case that even if environmental laws are passed, these are not enforced (Cao and Prakash 2010). Due to this, different authors have proposed international trade as a possible way to enforce climate policies (Aldy et al. 2001; De Melo and Mathys 2010; Zhang 2009) having the advantage that it would allow access to others' markets with low trade barriers (Nordhaus 2015).

The relationship between trade and the environment has been extensively studied.[3] Peters and Hertwich (2008) examine the flow of pollution through streams of international trade and determine the CO_2 emissions embodied in international trade for 87 countries. Depending on characteristics such as size and geographic location, a country's embodied emissions will vary. The authors discuss policies such as the formation of a coalition, in which countries commit to binding agreements to diminish the effects that trade may have on global climate policies.

Networks are ubiquitous in economics.[4] Kagawa et al. (2013) make use of networks to identify clusters of CO_2-intensive industries in the automobile supply chains. Vega and Mandel (2018) analyze through a network model the role of wind energy technology transfer in mitigating climate change and ways to speed up this process. Different works have been conducted relying on networks to analyze diffusion processes.[5] Our model is based on Morris (2000), which studies how the behavior from an initial small group can spread to the rest of the population. This is characterized as a local interaction game in which a player's binary choice is a best response to her neighbors' actions from the previous period. Once a critical threshold, the relative frequency of connections between players from a given group compared to non-members, is surpassed, this behavior disseminates throughout the network.

Because climate change is a global externality, it requires the collaboration and participation of the whole international community in order to be tackled swiftly and in the least costly way in terms of its impact on the economy, society and the environment (Stern 2008). Taking this into consideration, this paper makes different contributions. First, through the network model we highlight the expansion of the climate club that took place throughout different European countries and the order in which this happened. We consider two different thresholds and compare the predicted outcomes. Notice that without the thresholds, the expansion either occurs in one period or it does not occur at all. Furthermore, thresholds play a role in limiting or accelerating the speed at which the club expands, allowing us to model the occurrence of events.

Second, we relate the expansion of the club to the thresholds that determine best response dynamics. This can be interpreted as both obtaining membership in the club and as receiving special benefits from the club members' markets (i.e. mutually advantageous terms of trade). Our model differs from the original model of Morris (2000) in that we work with a finite, directed graph with weighted links, whereas the original one relies on a lattice with unweighted and undirected links. We develop, additionally, an alternative threshold that works well with weighted complete graphs. We then compare the results derived from it to those from the first threshold.

Finally, we show that the expansion of the club can be accelerated by a centralized mechanism wanting to device optimal targeting strategies, by considering the network structure and the number and position of the "seeds" or initial club members. The literature on the role of influential agents in the context of local interactions has been extensively studied in various fields such as physics (Bagnoli et al. 2001), computer science (Kempe et al. 2003; Kempe et al. 2005), marketing (Kirby and Marsden 2006) and economics (Galeotti and Goyal 2009; Tsakas 2017). To the best of our knowledge, this type of analysis hasn't been applied to this problem.

3. Data and Methodology

To test our model and its thresholds we use data of bilateral trade, for the EU, from the IMF's direction of trade statistics (DOTS). Specifically, the data are for "Exports, FOB to Partner Countries" in millions of U.S. dollars. These data are publicly available.

We organize the data into adjacency matrices of the network, with a matrix per year under study.

From this, we can create the links of the network representing the trade relations between each of the different trading partners. Specifically, the ij elements of the adjacency matrix represent the amounts in dollars of export flows between trading partners i and j. In our model, nodes or countries are "adjacent" if they are connected with each other through trade. In other words, nodes are "neighbors" if they are directly connected with each other regardless of whether they are physically next to each other or not. Thus, the outgoing directed links of the network point to the destination of exports while nodes act as countries.

The dataset for climate change mitigation policies implemented by the European countries comes from the European Environment Agency, and is publicly available. This database has very detailed information regarding the names and types of policies, which countries implemented or adopted them, year this occurred, etc. It also details whether these policies are related to a Union policy or not. We omit Bulgaria, Lithuania and Luxembourg from the list of countries we analyze since their data are not complete for some years. In the next section we explain the criteria used to filter these policies. The simulation routine was programmed for and implemented through R version 3.4.1 (R Core Team 2017), relying on the igraph package (Csardi and Nepusz 2006). The results were then contrasted with the environmental policy data.

4. Policies and Club Expansion

European countries have a long tradition in environmental protection policies. By the year 2011, a great amount of policies intended for reducing and abating GHG emissions had been adopted, implemented or planned by different countries. These ranged from waste reduction to alternative ways of efficient land usage. Furthermore, the EU has different climate and energy policy frameworks such as the Effort Sharing Decision (ESD), which covers areas such as transport and industrial processes. These set binding annual emission regulations at the national level and EU countries that do not comply may suffer sanctions. This works as a threat that deters countries from not reducing emissions. As an example, in more recent times both Germany and Ireland faced the prospect of sanctions due to their lack of reductions of emissions, with Ireland having to pay up to €600 million in penalties and Germany even higher amounts.

For the purpose of our study, we concentrate in policies that are related to GHG emissions derived from production and exports of goods and services. Due to the large number and ways these policies are categorized, we filter them according to the following criteria that must be simultaneously fulfilled:

1. The measure was either implemented or adopted and did not expire during the period under study.

2. The measure targets an energy supply source, an industrial process, some form of transportation and/or those that cut across different sectors (cross-cutting policies).

The first item's purpose is to keep consistency throughout the simulation, since we wish to unveil how the same set of policies were harmonized across European countries. Policies that expired mid-way through the period under study or that were replaced by others are not considered because the theoretical model assumes that harmonization cannot be reversed.

In the second item, energy supply refers to carbon capture and storage, efficiency improvement in the energy sector, etc. Industrial processes relate to the installation of abatement technologies, the control of fugitive GHG emissions, and so on. Policies associated to transportation include road taxes for high CO_2 emitting vehicles, improvement of the efficiency of vehicles, and the like. Cross-cutting policies associate to issues that cut across numerous environmental laws, regulations and/or programs. (e.g. energy efficiency throughout various sectors in the economy).

From the two criteria, the initial club members that we use to run the simulations are comprised of: Austria, Czech Republic, Denmark, Finland, France, Latvia, Netherlands and Sweden. Table 1 presents the order and year that EU countries began to harmonize policies, according to the criteria we used. All of the eight original club members had one or more environmental policies in place by the year 1996 (the initial period of the simulation).

First period (until 1996):
Austria (1995), Czech Republic (1995), Denmark (1993), Finland (1992), France (1982), Latvia (1993), Netherlands (1992), Sweden (1957).
Second period (until 2004):
Belgium (2004), Estonia (2001), Germany (2000), Greece (1998), Romania (2002), Slovak Republic (1997), Slovenia (2004), Spain (2003), Poland (1997), United Kingdom (2001).
Third period (until 2011):
Croatia (2007), Cyprus (2007), Hungary (2007), Ireland (2005), Italy (2007), Malta (2008), Portugal (2007).

Source: European Environment Agency

Table 1: Harmonization waves

For all countries to harmonize, we need to consider two aspects of the network that will affect the outcome:

1. The adoption threshold.

2. The number of initial seeds or climate club members and their positions.

The threshold establishes a condition or value that must be met so that the "virus" spreads from a node to another (i.e. action 1 is taken by neighboring nodes). As an example, suppose we have a star-shaped network of four players and that we rely on Equation 1 (in the appendix) with a value p of, say, 0.28. This means that a given player needs more than 28% of neighbors belonging to the climate club in order for her to harmonize. An example of said process is shown in Figure 1, in which 1/3 of neighbors (33%) were in the club.

Finally, the initial number of climate club members or seeds also determines the speed at which the club expands. Notice that seeds can be heterogeneous: The higher the eigenvector centrality[6)] they have, the higher their influence is.

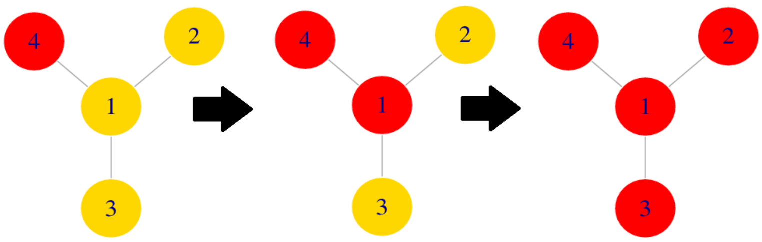

Figure 1: Example of expansion from player 4, the initial seed, with a threshold p=0.28

5. Results

We evaluate the two thresholds proposed and see which one does a better job at explaining the spread of the climate club in Europe for the period under study. For the first threshold (which considers the ratio of trading partners in the club to total trading partners), the higher p is, the harder it becomes for the club to expand. We find that for values of p lower than or equal to 0.333, all the countries harmonize inmediately (only one step or wave). This is expected because the network is complete (i.e. each player is neighbors with all other players).

By requesting that more than 33% of neighbors are part of the club, we observe that it takes more steps (waves) for it to expand. Between the threshold values of 0.334 and 0.363 it takes up to two waves. Once we go beyond this last value though, the model does not attain complete harmonization. Instead we reach a scenario of co-existent equilibrium, in which some countries belong to the climate club and others do not and remain in that state (i.e. only the initial seeds remain as members).

We define the hit rate of the thresholds as the percentage at which the model is able to correctly reproduce the real events it is describing. The predictive power of the first threshold is very low, having a hit rate below 50% across different values of p. This is presented in Figure 2 along with the distribution of prediction hit rates for p. A graphical representation of the club expansion process is depicted in Figure 3. Red nodes represent countries that have harmonized and yellow nodes represent countries that have not.

To compute the hit rate for this threshold, we compare the results obtained from the simulation with the data shown in Table 1. We then proceed to count the number of countries that are correctly predicted through the simulation. Finally, we divide that value by the total number of countries from the first and second wave (i.e. the countries that are not initial seeds).

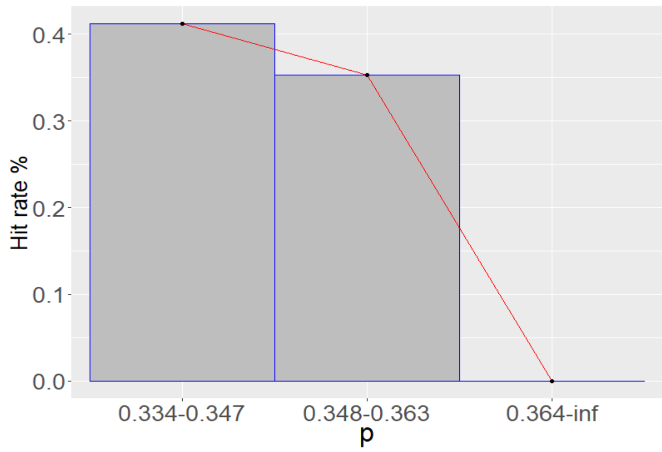

Figure 2: Distribution of hit rates for threshold 1

Since we are dealing with a complete graph, every node has the same degree and thus the degree distribution of the network does not help in understanding the order of the harmonization waves. Threshold 2 then takes into account the weight of links in addition to the number of neighboring nodes. This incorporates the fact that some partners are more influential than others, given the volume of their trade exchange. Under this threshold, behavior is also different. The parameter η reflects the importance of exports to countries that belong to the club with respect to those that do not: a higher value of this parameter gives more weight to these markets by the target country, allowing for a greater chance that it decides to harmonize. The importance granted to these countries reflects the added benefits of being a

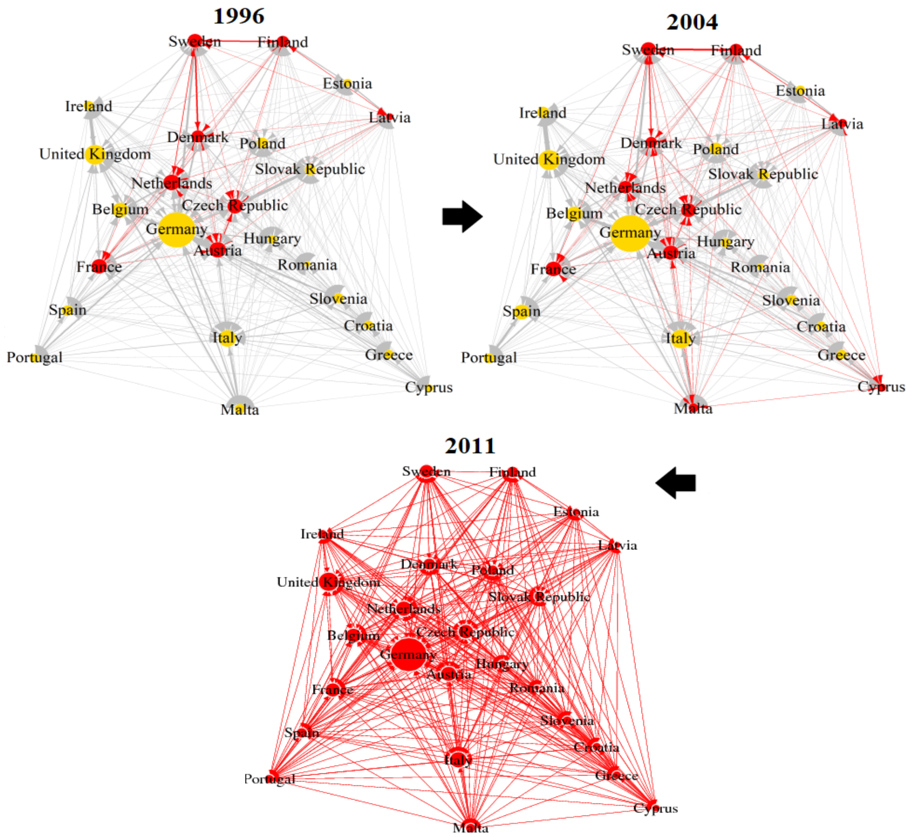

Figure 3: The club's expansion process for threshold 1 with $p \in [0.334, 0.347]$

part of the club that are not directly related to the trade flows (e.g. lower or no taxes to capital flows, free movement of people within the club's territory).

For an η of 1.09 or higher, complete harmonization always occurs.[7)] When the threshold's parameter takes a value between 1.48 and 2.27 the model has an average predictive hit rate, with respect to the expansion of the climate club in Europe, above 60%. This is more accurate than in other cases. The distribution of hit rates is depicted in Figure 4. We can observe that the hit rate is highest (71%) for the interval going from 1.75 to 1.90. A graph for this is shown in Figure 5. We calculate the hit rate for this threshold in the same way as in the previous case.

To check the results of this threshold we test the network's robustness by using a null model. We do this for the second network (club expansion up to the year 2004) by shuffling 5 links with their corresponding weights such that the row totals remain unaltered. We then run 1000 simulations to finally contrast the outcomes with those of the original network. Additionally, we assess the statistical significance of the hit rate when $\eta \in [1.75, 1.90]$. By doing this, we see if the network is sensitive to the

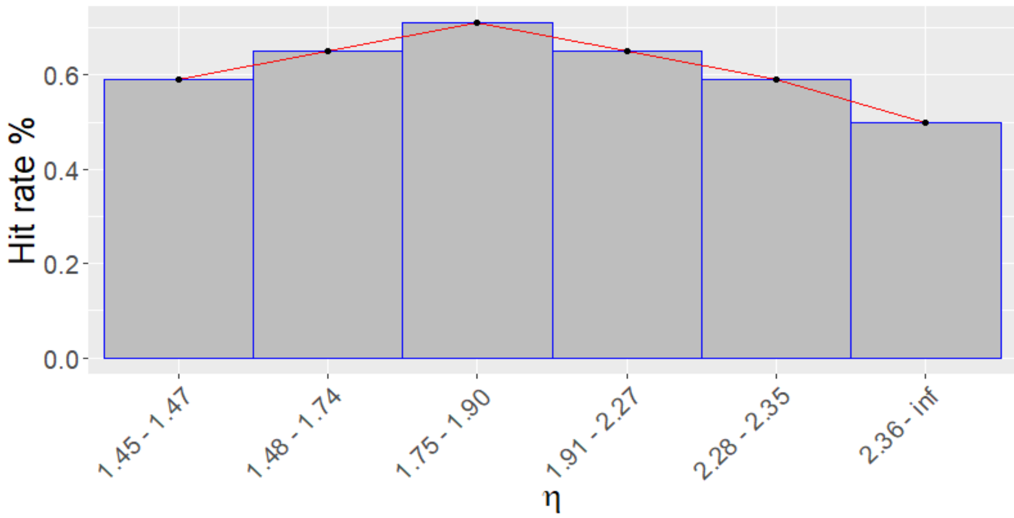

Figure 4: Distribution of hit rates for threshold 2

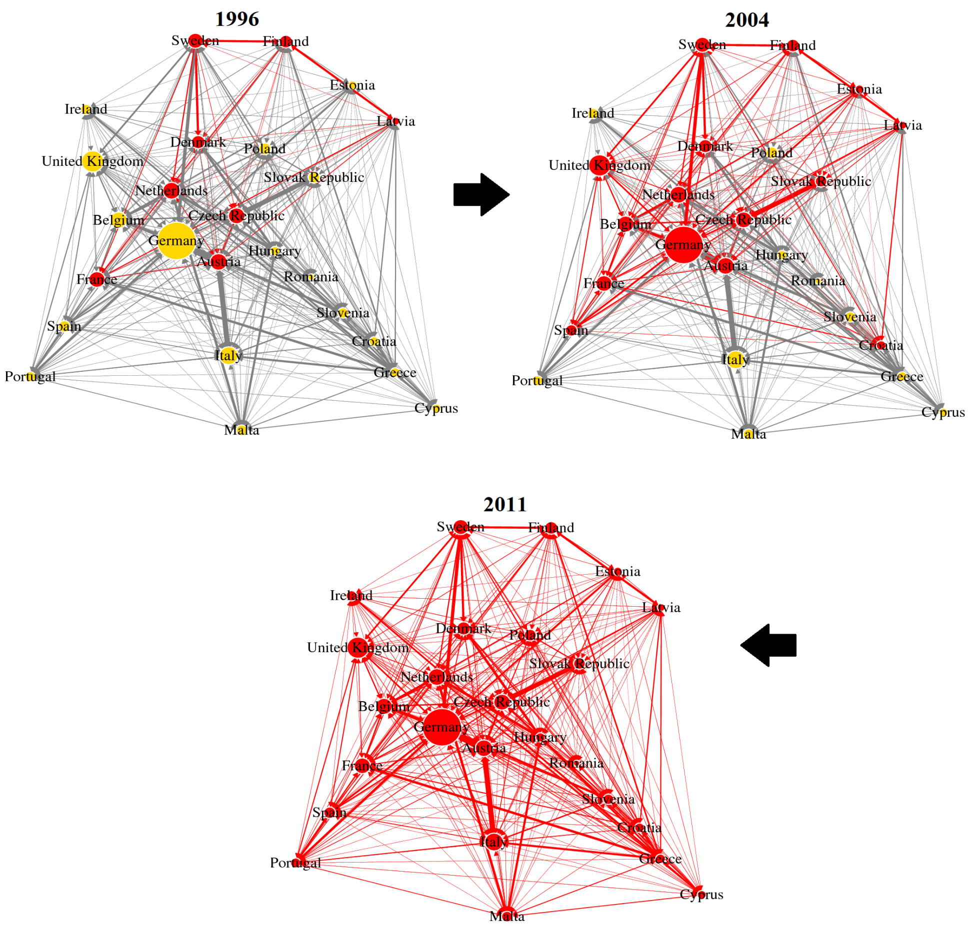

Figure 5: The club's expansion process for threshold 2 with $\eta \in [1.75, 1.90]$

introduction of a small “perturbation”. If the perturbation does not alter the contagion process significantly, then the network is robust. We find that when η takes the above values, the model predicts with a hit rate of 70% in 786 out of the 1000 simulations. In other words, after randomly exchanging links of different nodes, the model is able to predict with a high degree of accuracy the expansion of the climate club. This is shown in Figure 6. Additionally, when we run simulations for the extreme case, (i.e. all nodes with all their links being shuffled), we find that the 70% hit rate of η occurs in less than 15% of the simulations. This confirms that this hit rate is not due to some structural property inherent to the network. The network is then robust.

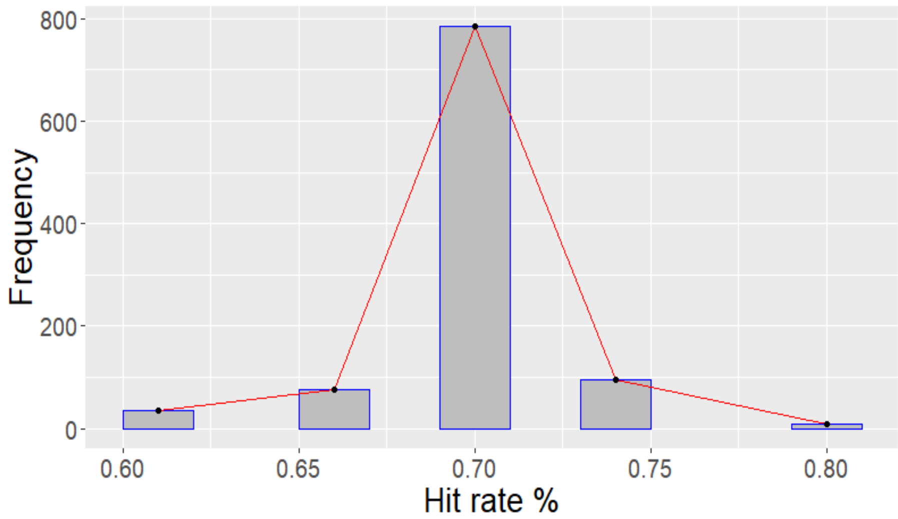

Figure 6: Null model after Shuffling 5 links

Now we ask, what would the situation be had the initial seeds been different ones? Given this network, which countries would have the highest influence for the club to expand? The use of simulations allows us to do counterfactual analyses and helps us respond these questions. First we detect the initial injection points (seeds) and then check how fast the expansion process is compared to how it previously was.

To find the best "diffusors of the virus", we search for the most influential countries in the network. For this, we rely on the eigenvector centrality and consider the nodes with the eight highest scores (i.e. the eight countries with the highest rankings in this measure). Germany, France, United Kingdom, Italy, Netherlands, Belgium, Spain and Sweden obtain the highest scores, in that order, and thus are taken as the initial seeds. When we use them and apply the same η values from threshold 2 as before, the climate club’s growth process takes a single step instead of two, spreading to the rest of the network in that time. This informs us that, indeed, these countries have a high influence and power in the network, being markets that are very attractive to others.

If we alter the number of best diffusors while maintaining the threshold's value constant, then the number of waves in the club's expansion process also changes. What is the minimum number of countries in the club that is needed for complete club harmonization in this network to happen? From the list of eight best diffusors previously obtained we begin omitting countries gradually, from least to most influential, until we reach said minimum number. We find that for an η between 1.75 and 1.90 (for which the prediction hit rate is the highest), only one country, Germany, is sufficient for complete club harmonization to materialize. When we do the same for a threshold value of 1.09 (the minimum value at which complete club harmonization occurs in this network), two countries are necessary: Germany and France.

These results tell us that by understanding and taking into consideration the underlying structure of the network, a centralized mechanism can accelerate the expansion of the climate club. This process can additionally be attained at a wide scale (e.g. regional or world-wide). Since some countries have a higher centrality and weight in the expansion of the climate club, our results show that it matters who the original seeds are and that they can have a definite role: The more central their position in the network is, the higher their influence on others will be. Heal and Kunreuther (2017) also obtain results similar to ours. These authors find that the minimum number of countries necessary in a climate club, for a wide international climate agreement to take place, is two.

The second threshold shows us that under minimum binding sanctions (as in the case of non-tariff trade barriers), the links representing exports are important for European countries concerning the decision of adopting environmental regulations, regardless of whether these countries actually joined the club or not. In other words, once the model takes into account the importance of export markets, it predicts the sequence of policy adoption better.

A climate club should thus be designed with policies that can be implemented with ease and that have a universal appeal (i.e. those that do not depend on or consider only specific characteristics of each country), while being efficient and stable. All this could be achieved through threats from member countries to non-members of imposing either non-tariff trade barriers (an example being imposing additional procedures for importing goods from non-members) or canceling subsidies/international aid to them. Additionally, a club could provide club goods such as mutually advantageous terms of trade and investment, joint R&D programs in renewable energy technology and extension of pipelines or electricity grids to mutually enhance energy security, thus creating incentives for non-members to join it.

Our results imply that, for the case of the EU, Germany and France are essential to achieve this kind of outcomes by acting as initial club members and by threatening to sanction non-members due to their market size and importance.

Owing to large costs associated with developing and deploying green energy technologies, joint research, development and collaboration between different countries can be a way to accelerate its implementation. By being the “pioneers” in the climate club, big-market countries can have a first-mover advantage in the joint development of these technologies, giving them a lead over non-members on these technologies. This could serve as an incentive for countries such as Germany and France to be the “initial diffusors” in our model. Once these countries joined the club, it would become easier for negotiations to tip and more countries would be pressured therefore to become members (accelerating the “contagion process”), while non-members would not be able to free-ride on other countries’ effort for global public goods. This type of mechanism could help achieve more satisfying outcomes than voluntary agreements between countries.

6. Conclusions

We investigate how the expansion in the harmonization of climate policies across countries can occur and how this is affected by the trade linkages between trading partners. A region such as Europe, with a large pool of climate change policies in effect, serves as a reference point to understand how tightly connected countries can have incentives to join and expand a climate club.

The contribution of the paper is studying this issue through a network approach in which nodes represent European countries taking one of two actions: join a climate club through harmonization or not, based on the trade flows with their trading partners. We use two alternative thresholds that determine best response dynamics. By means of simulations, these thresholds provide an interpretation to the pattern in which different countries in Europe joined the climate club. Through these simulations, we can observe how the expansion of the club occurred and in how many waves this happened.

We find that the second threshold proposed —which considers the importance that exports to countries that belong to the climate club have in comparison with those that are not members of it— does a good job at matching the order in which European countries joined the club, for the period comprising the years 1996-2011. When testing for countries in the network that make the best diffusors, we observe that the minimum number required to trigger a complete club harmonization process is only between 1 and 2. This is in line with previous findings that as few as two countries may foster an international climate agreement by shifting behavior from a given equilibrium to a different one. These results suggest that there may be key or influential players in the network that should be considered in order to accelerate the expansion of the club in a more effective way. When taken at a world-wide scale, these countries can make the difference in tipping negotiations in one direction and obtaining better results in cases in which fast actions are necessary, such as in the case of climate change.

Based on the previous idea, it is possible that these influential countries can actually demand or stipulate that other countries comply with the requirements of harmonizing their environmental policies under the threat of not getting access to the climate club or its benefits.

For future research, we think that the model could be expanded by letting externalities play a role in these relations. By doing so, it would be possible to have a better understanding of the impact that policies have on the emissions generated by various economic activities throughout Europe and other regions of the world. Also, since our model lacks sanctions, explicitly considering them through some kind of variable that captures its effects on player behavior would be an interesting addition to the model, allowing for further insights from the simulations.

7. Appendix

The Model

Assume a finite set of players $N = \{1,...,n\}$, with $n \geq 3$. The players in our model represent European countries. We denote a directed network $\mathbf{g}$ through an adjacency matrix in which each link connecting a node $i \in N$ is given by a (row) vector $\mathbf{g}_i = (g_{i1},...,g_{ii-1},g_{ii+1},...,g_{in})$, where $g_{ij} \in \{0,1\}$ for each $j \in N \setminus \{i\}$ and let $g_{ii} = 0$. Let $\mathbf{g}_i \in G_i = \{0,1\}^{n-1}$. We say player i has a link with player j if $g_{ij} = 1$. The links in the network represent the trade that countries perform with each other.

We define the set of players to which player i has links with as $N_i^{OUT}(\mathbf{g}) = \left\{j \in N : g_{ij} = 1\right\}$, while the out-degree of player i is given by $d_i^{OUT}(\mathbf{g}) = \left|N_i^{OUT}(\mathbf{g})\right|$. Note that the network of links $\mathbf{g}$ is a digraph or directed graph. We denote its closure as $\bar{\mathbf{g}} = cl(\mathbf{g})$: an undirected graph for which $\bar{g}_{ij} = max\left\{g_{ij}, g_{ji}\right\}$ for each $i,j \in N$. In other words, we substitute each directed link in $\mathbf{g}$ for an undirected one. Additionally, let $N_i(\bar{\mathbf{g}}) = \{j \in N : \bar{g}_{ij} = 1\}$ be the set of players to which i is connected in the undirected graph $\bar{\mathbf{g}}$. Let $d_i(\bar{\mathbf{g}}) = |N_i(\bar{\mathbf{g}})|$ be i's degree in said graph.

We say that a player has two possible actions she can take, 0 and 1. Denote $u(a, a')$ for a player's payoff from a specific interaction if she chooses a and her neighbor chooses a'. This payoff function refers to the Figure 7 below:

	0	1
0	q, q	$0, 0$
1	$0, 0$	$1-q, 1-q$

Figure 7: Payoff matrix

where payoffs are parameterized by $q \in (0,1)$, so that action 1 is a best response (BR) for a given player if she assigns a value of at least q to the other player also choosing action 1.

At any given period of time, each player i will take an action $a_i \in \{0,1\}$. Let $R \subset N$ be the set of agents taking the same action, say 1, and $R^C = N \setminus R$. Then, each player in R must have at least a fraction $q \in (0,1)$ of her neighbors in R, and also each player in R^C must have a fraction of at least $1-q$ of her neighbors in R^C.

Each player maximizes her instantaneous utility. The instantaneous utility considered in this model depends on the trade achieved by each player with her trading partners: The higher the volume, the greater the utility. This interpretation should be understood in a wide sense: It includes economic considerations because, as international trade has similar effects as discovering new technologies, it is total-welfare enhancing; and it also includes political considerations because the probability of being reelected increases as the economy improves.

Following Morris (2000), we define the *configuration* function $s : N \mapsto \{0,1\}$. Given s, player i's BR is to select an action such that it maximizes the sum of her payoffs from the interaction with each of her neighbors. Given $\bar{\mathbf{g}}$, we say a is a BR for player i if:

$$\sum_{j \in N_i(\bar{\mathbf{g}})} u(a, s(j)) > \sum_{j \in N_i(\bar{\mathbf{g}})} u(1-a, s(j))$$

Analogously, given $\mathbf{g}$ we say $\tilde{a}$ is a BR for player i if:

$$\sum_{j\in N_i(\mathbf{g})} u(\tilde{a}, s(j)) > \sum_{j\in N_i(\mathbf{g})} u(1-\tilde{a}, s(j))$$

Note that both a and $\tilde{a}$ are binary actions.

It follows that for player i action 1 is a BR if a proportion higher than q of her neighbors choose it as well. In the same way, action 0 will be a BR if a proportion higher than $1-q$ of her neighbors take it. A given configuration s is identified with the subset $R = \{i : s(i) = 1\}$; and the subset R is identified with configuration s where

$$s(i) = \begin{cases} 1 & \text{if } i \in R \\ 0 & \text{if } i \in R^C \end{cases}$$

The thresholds

In the model, countries join the climate club when a certain threshold is surpassed.[8)] Depending on whether this is fulfilled or not, players will respond with action 1 or 0, respectively. We proceed to define two alternative versions of this rule, based on different possibilities:

1. The cohesiveness of R. A subset R is p-cohesive with respect to $\bar{\mathbf{g}}$ if each player in R has at least a fraction p of its neighbors in R. In other words, a player's BR is given by:

$$a(N_i(\bar{\mathbf{g}}), R, p) = \begin{cases} 1 & \text{if } \dfrac{|N_i(\bar{\mathbf{g}}) \cap R|}{|N_i(\bar{\mathbf{g}})|} > p, \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

   with $p > 0$.

   Equation 1 reflects that countries have a higher incentive to harmonize policies as the number of neighbors harmonizing increases.

2. The relative importance between partners that belong or not to the climate club. Specifically, we consider that a player joins the club if the exports to trade partners belonging to it is greater, by a magnitude η, than those to partners out of it, for a given period t:

$$\tilde{a}_t\left(N_i\left(\mathbf{g}\right), R, \eta\right) = \begin{cases} 1 \quad \text{if } \eta > \dfrac{\sum_{j \in R^C} \left|N_i^{OUT}\left(\mathbf{g}\right) \cap R^C\right| w_{ij}}{\sum_{j \in R} \left|N_i^{OUT}\left(\mathbf{g}\right) \cap R\right| w_{ij}} \\ 0 \quad \text{otherwise} \end{cases} \tag{2}$$

$\forall t > 0$ and $\eta > 0$ and w_{ij} representing the weights of the outgoing links from player i to her neighbors. The t subscript represents the fact that an action a player will take may change from a period compared to the previous one since the network's weights may vary. This is only if a switch in behavior hasn't happened, since there is no reversal from action 1 to 0. Note that for the case of the directed network $\mathbf{g}$, we adapt the concept of cohesiveness to include the specific weights of the links. Equation 2 reflects that not all partners are equally valuable: If the flows (i.e. volumes of trade) are larger with members of the club, the incentives to harmonize increase.

As a note, equation 2 assumes that by becoming club members, countries have implicitly taken into consideration the costs and benefits of joining or remaining out of the climate club. This includes the sanctions for not complying to its rules once they are members. Losing access to important markets or having higher trading barriers would not have good economic consequences, so they decide to harmonize climate policies with their trading partners in the club.

Steady State

Since we are dealing with a game of strategic complements, we know it is well-behaved. We summarize below the theoretical equilibrium predictions for the first threshold (proposed by Morris 2000). The second threshold, which we propose, is only tested through simulations.[9)] We do this in section 4 and compare its results with those from the first one. To the best of our knowledge there are no formal results for this kind of threshold:

Proposition 1 (Jackson and Zenou 2015)**.** *Assume a network $(N, \bar{\mathbf{g}})$ and a game as the one previously described. An equilibrium where action 1 is played by $R \subset N$ players and action 0 is played by R^C*

players exists if and only if R is q-cohesive and R^C is $(1-q)$-cohesive.

This proposition tells us that depending on the proportion of players in each set, different combinations of actions will be taken throughout the network. This allows for "co-existent equilibria" in which some players choose action 0 while the remaining players choose action 1.

If there are some players in R who, by acting as the initial seeds, make all players switch from taking action 0 to 1 under a BR, we say that there was a *contagion* from R. To keep consistency with the definitions we use in this work we will refer to this as a complete harmonization by the players in the network. A set R is defined as *uniformly no more than p*-cohesive if R has no nonempty subset that is more than p-cohesive.

Proposition 2 (Jackson and Zenou 2015)**.** *Assume a network $(N, \bar{\boldsymbol{g}})$ and a game as the one previously described. There will be contagion from R if and only if R^C is uniformly less than $(1-q)$-cohesive.*

III. Industrial Productivity Divergence and Input-Output Network Structures: Evidence from Japan 1973–2012[10)]

Abstract

Since the early 1990s, there have been larger and increasing labor productivity differences across industries in Japan. More specifically, a clear pattern of sigma and beta divergence across industries is observed. To shed light on these stylized facts, we first evaluate the input–output structure of Japan through the lens of a community-detection algorithm from network theory. Results from this analysis suggest the existence of two input–output network structures: a densely-connected group of industries (a stationary community), whose members remain in it throughout the period; and a group of industries (a transitional community) whose members do not belong to this first group. Next, we re-evaluate the industrial divergence pattern of Japan in the context of each network structure. Results suggest that divergence is mostly driven by the transitional community. Interestingly, since 2007, a pattern of sigma convergence started to re-appear only in the stationary community. We conclude suggesting that industrial divergence and instability in community membership are not necessarily indicative of low productivity performance.

Keywords: Communities; Input-output networks; Productivity; Convergence analysis

1. Introduction

When analyzing the aggregate data of an economy regarding its growth performance, it is not possible to determine which sectors are leading this trend. By working with partitioned data, we can study the differences in productivity across groups while also obtaining some insights about different trends throughout the aforementioned sectors. By working with partitioned data, we aim to uncover important heterogeneous outcomes that could be masked when using wider data aggregations.

In this paper we first show that, since the early 1990s, there have been larger and increasing labor productivity differences across industries in Japan. This raises the question of whether there could be a group or cluster of industries whose productivity is behaving differently from that of the rest of the economy. Community detection algorithms from network science allow us to deal with these kind of issues through the partitioning of a network into smaller subsets. Fortunato and Hric (2016) define a community as a subnetwork whose nodes have a higher probability of being linked to other nodes in the subnetwork than to any of the remaining nodes of the network. In our paper, nodes represent industries and links between them constitute the trade that they perform. Input–output tables can be translated as directed weighted networks.[11)]

By relying on input-output data from the Japanese Industrial Productivity Database of the Research Institute of Economy, Trade and Industry (RIETI), our interest in this paper is twofold: First, what kind of input–output network structures (industrial communities) characterize the Japanese economy? Second, to what extent is the productivity of the members of each network community converging?

Techniques to detect network communities have a long history. Girvan and Newman (2002) and Newman and Girvan (2004) proposed a simple yet powerful method to find these type of structures within networks, and since then the literature has grown enormously. More recently, other methods to detect communities such as Degree-corrected Stochastic Block Models (Karrer and Newman, 2011) and the Louvain method (Blondel et al., 2008) were developed. Good surveys on these literatures are Fortunato (2010) and Fortunato and Hric (2016).

The analysis of economic structures and sectors dates back to the 1940s with the foundational analysis of Leontief (See for example Leontief (1944)). Even though the economic structure into sectors of an economy is related to a network, it is not the same as a social network. Both economic sectors and social networks can be graphed and understood through the use of nodes and links, but their interpretation is different. Social networks rest on behavior, incentives and relationships between the actors or agents under study; economic sectors build upon market and technological requirements and their structure is more stable.[12)]

Although social networks play a traditional role in the literature, there is an emerging literature such as Acemoglu et al. (2012), Acemoglu et al. (2016) and Carvalho (2014) that in recent years use input–output data and networks to understand macro patterns and their fluctuations. Other authors as Kagawa et al. (2013) and Cerina et al. (2015) find network communities of industries in input-output tables by employing alternative community detection methods. Zhu et al. (2014) study the international trade network through a community detection algorithm and analyze the relationship between globalization and regionalization. del Río-Chanona et al. (2017) study the World Input Output Network, concentrating on the importance that countries or sectors have and find that these break into two groups: one group based on renewable resources and the other into non-renewable ones.

In order to detect clusters of industries in the Japanese economy, we employ the leading eigenvector algorithm for community detection developed by Newman (2006). This method consists in utilizing the leading eigenvalue and eigenvector of the modularity matrix to perform a spectral optimization of the modularity index, developed by Newman and Girvan (2004). An advantage that network portioning has is that when detecting clusters of industries, the limits between groups can be established based on measure such as the modularity index. The optimization performed by the modularity finds groups strongly connected by maximizing the connections of members inside the community while minimizing the connections between different groups. The problem is that this method can be computationally demanding. The method by Newman (2006) is computationally more efficient than other algorithms.

The first step of this procedure involves calculating the leading eigenvector of the modularity matrix and then partitioning the network into two. This is done in a way that the splitting maximizes the modularity index by relying on the leading eigenvector. This process is iterated and it re-partitions the network at each step until the modularity index is no longer positive. The resulting groups from these partitions consist on the communities that are detected.

Through this algorithm, we detect a stable community for the whole period under study. Because sometimes members of a community "leave" and/or "join" it in different years, it becomes difficult to derive results from communities in an intertemporal fashion due to a lack of consistency in their composition. Therefore, we proceed to define a different type of community, which we call the *stationary community*. It results from the intersection of members of a given community throughout the entire period. In other words, the stationary community consists only of members that remain "inside" the community for the entire period under study: 1973–2012. This allows us to examine only the industries that belong to a community and compare their performance with those of other communities or that belong to none at all. To the best of our knowledge, this has not been done before.

The community we obtain is composed of 44 out of 108 industries of the economy. These industries consist largely of globally non-tradable goods, such as local services. Although it is not clear-cut, by largely we mean that the ratio of services to non-services is higher in the stationary community. This is due to limitations that community detection algorithms sometimes have in avoiding the overlap of some communities. This is an ongoing research in the field of network science and is being worked upon (see for example Fortunato and Hric (2016) for further insights). We collect the remaining sectors of the economy into what we call the transitional community, the complement of the stationary community.

Given these two kinds of groups, we next evaluate to what extent the productivity of the members is converging. The study of economic convergence has been at the center of the modern literature on economic growth and development at least since the seminal work of Solow (1956). The empirical literature on economic convergence that started with the seminal work of Baumol (1986) has rapidly evolved in the last three decades.[13)] Among the early pioneers, Barro and Sala-i Martin (1992a) studied convergence across countries, Barro and Sala-i Martin (1992b) focused on regional convergence, and Bernard and Jones (1996) focused on industries. Compared to cross-country convergence, regional and industrial convergence are more likely to be expected. This is because the regions and industries of a country are more likely to share common institutional and technological environments. Furthermore, labor mobility across regions and industries acts as a powerful force for convergence.

When applied to the whole economy, the classical convergence analysis of Barro and Sala-i Martin (1992a) suggests that Japan is characterized by two distinct productivity eras. On the one hand, the 1973–1990 period is characterized by a clear pattern of labor productivity convergence across industries; on the other, the 1990–2012 period is characterized by increasing productivity dispersion and a process of industrial divergence. When applied to the two kinds of network communities, the convergence analysis suggests that in more recent years, at least, overall divergence appears to be driven by the divergence patterns of the transitional community. Interestingly, since 2007, a pattern of convergence started to appear only in the stationary community.

The rest of the paper is organized as follows. Section 2 describes the methods and data. Section 3 presents some overall facts about productivity dispersion and industrial divergence in Japan. Section 4 shows the results of the convergence analysis for each network community. Finally, Section 5 offers some concluding remarks with suggestions for further research.

2. Methods and Data

(1). Input-Output Network Analysis

In order to partition the input-output data into communities we made use of the modularity index, which is defined as:

$$Q = \frac{1}{4m} \sum_{ij} \left[A_{ij} - P_{ij}\right] (s_i s_j) \tag{3}$$

where m is the number of links in the network, A_{ij} is the adjacency matrix and $(s_i s_j)$ takes a value of 1 if i and j belong to the same group or a value of -1 otherwise. Additionally, we define $P_{ij} = \frac{k_i k_j}{2m}$, where k_i is the degree of node i. There are $2m$ link ends in the network so the probability that a node j is attached to one end of these is $\frac{k_j}{2m}$, and the expected number of links between nodes i and j is given by P_{ij}. The whole equation is divided by $4m$ so that it is normalized to the interval $[-1,1]$.

We can rewrite (1) as:

$$Q = \frac{1}{4m}\mathbf{s}^T\mathbf{B}\mathbf{s} \tag{4}$$

Q is a measure of assortative mixing in the network.[14)] Positive values imply assortativity while negative ones indicate disassortativity. The matrix **B** is a real symmetric matrix called the modularity matrix and it works in optimizing the modularity index, while the vector **s** represents an eigenvector of **B**. The modularity matrix is defined as:

$$B_{ij} = A_{ij} - P_{ij} = A_{ij} - \frac{k_i k_j}{2m}. \tag{5}$$

To obtain the maximum modularity, the vector **s** is utilized. This vector is set proportional to the eigenvector $\mathbf{u}_1$, which corresponds to the dominant eigenvalue of **B**. For this, a value of +1 is assigned to the ith elements of $\mathbf{u}_1$ having a non-negative value and a value of -1 is given otherwise. These two options represent the partition in which the node related to the i-th element will be placed. This process is iterated until the modularity is no longer positive, that is, there is no more positive assortativity.

(2). Stationary and Transitional Communities

The method by Newman (2006) detects communities only for a network at a given time. Since we are working with many years (i.e., a network per year), the members of the communities may change throughout time. In other words, they could "enter" and "exit" a given community a number of times in the period under study. Therefore we need to define what a community is for the case of an intertemporal or evolving network. Ideally, members of a given community should remain in it for the period of time that we are interested in analyzing. We will call this type of community a *stationary community* which we define as:

$$SC_i = \bigcap_{t=0}^{n} C_{i,t}, \text{ with } C_{i,t} \text{ being community } i \text{ in year } t. \tag{6}$$

Equation 4 tells us that members that remain in the same community for every year under study, will form the stationary community. If even for a single year a member is not present, then it will not be considered a part of the stationary community and will be excluded from it. Nodes that do not belong to a stationary community are considered part of the *transitional community* or, in set-theoretical terms, the complement of the stationary communities. We note that the transitional community is not a community in the traditional definition, but simply a way for us to compare it with the stationary community.

(3). Sigma and Beta Convergence Analysis

The work of Sala-i Martin (1996) highlights the importance of two classical summary measures of convergence: sigma and beta convergence. In the context of our paper, the former refers to the reduction of productivity dispersion across industries and the latter refers to the existence of catch-up effects (that is, the extent at which unproductive industries are catching up with the more productive ones). Furthermore, as shown by Furceri (2005), these two measures are closely related. To attain sigma convergence, beta convergence is a necessary condition, yet it is not a sufficient one.

More specifically, sigma convergence is commonly measured by either the standard deviation of the logarithm of the variable under study (labor productivity in the case of this paper) or by its coefficient of variation. In this paper, we use the former and define it as follows:

$$\sigma_t \equiv \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(log\left(x_{i,t}\right) - \overline{log(x_t)}\right)^2}, \tag{7}$$

where σ_t is the labor productivity dispersion across industries at time t, N is the number of industries in the sample, $x_{i,t}$ is the labor productivity of industry i at time t, and $\overline{log(x_t)}$ is the average of the natural logarithm of industrial labor productivity at time t.

Beta convergence in its simplest form[15)] indicates the inverse relationship between the growth rate of a variable and its initial level. In this paper, we estimate this relationship as follows:

$$\frac{1}{t}\,log\left(\frac{x_{i,t}}{x_{i,0}}\right) = \alpha - \frac{\left(1-e^{-\beta t}\right)}{t}\,log\,x_{i,0} + u_t, \tag{8}$$

where the term in the right side of Equation 6 is the average annual growth rate of labor productivity in industry i, β is the speed of convergence, $x_{i,0}$ is the initial level of labor productivity, and u_t is a random disturbance.

(4). Data

For our analysis we relied on the input–output tables of the Research Institute of Economy, Trade and Industry (RIETI). More specifically, we use the 2015 version of the Japanese Industrial Productivity Database (JIP Database 2015). Covering Japan's economy over the 1970–2012 period, this database contains information about 108 industries.[16)] However, in order to construct a balanced panel dataset, the 1973–2012 period was evaluated. The labor productivity analysis was also based on this database. In particular, the series of gross real output and the number of workers were used to compute the labor indicator used in the paper.

Recent labor productivity studies have used the total number of work-hours to compute a more intensive measure of labor productivity. Thus, one could question the use of the number of workers in the computation of labor productivity. Yet, in our database, at least, it turns out to be that work-hours and the number of workers were highly correlated. For instance, the correlation coefficient between these two indicators was 0.98 and 0.99 in 1973 and 2012 respectively. Moreover, this high correlation has been stable over the entire 1973–2012 period. Thus, from an empirical standpoint, the selection of any of these indicators may not drastically affect the robustness of the results, particularly for the time trends.[17)]

Since the community detection algorithm of Newman (2006) worked better with undirected and unweighted networks, we constructed networks with these characteristics from the Input-Output tables for each year we study. First, we symmetrized the data in the matrices. For this, we added each matrix with its transpose and we replaced with zeros the main diagonal of the matrices we obtained.[18)] Finally, we replaced the positive entries in the matrices with ones and with zeros any entries that have negative values or zeros.

3. Some Stylized Facts: Productivity Dispersion and Divergence

Figures 8 and 9 document both the overall increase in labor productivity and the increase in its dispersion across industries. Panel (a) of each figure measures labor productivity as the ratio of industrial value-added (in millions of yen, 2000 prices) to the number of workers; panel (b), on the other hand, is based on the ratio of industrial gross output (in millions of yen, 2000 prices) to the number of workers. The increase in labor productivity dispersion is most noticeable and systematic in Figure 9b. In this figure, labor productivity is measured as the median gross output per worker and its dispersion is computed as the inter-quartile range (IQR).

Compared to the other three figures, Figure 9b is particularly more informative for the following two reasons. First, both the median and the IQR are less sensitive to extremely large or small values (outliers). Second, compared to value-added, gross output does not contain negative values. Positive values are required for the convergence analysis since it is based on the logarithm of output.

Figure 10 shows a U-shaped pattern that summarizes the convergence-divergence dynamics of industrial labor productivity in Japan. The dotted line indicates the actual evolution of the industrial dispersion. The solid line is a polynomial regression fit. Following previous studies on sigma convergence, the dispersion was measured as the standard deviation of the logarithm of output, which in this case is gross-output per worker. Given these measures, it was clear that most of the post-war history of industrial productivity in Japan was characterized by two distinct eras. On the one hand, as the dispersion decreased in the 1973–1990 period, there was a clear process of productivity convergence. On the other hand, as the dispersion increased in the 1990–2012 period, there was also a clear process of productivity divergence, which appears to be slowing down in more recent years.

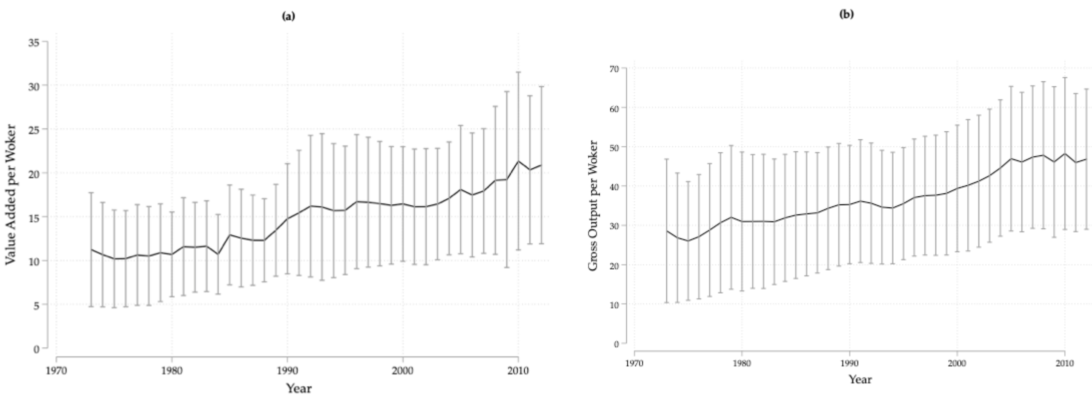

Figure 8: Mean labor productivity and dispersion (standard deviation).

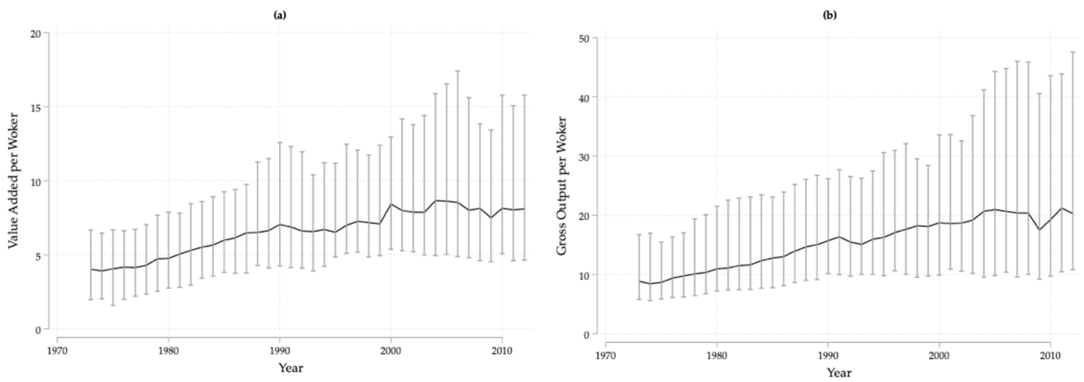

Figure 9: Median labor productivity and dispersion (inter-quartile range).

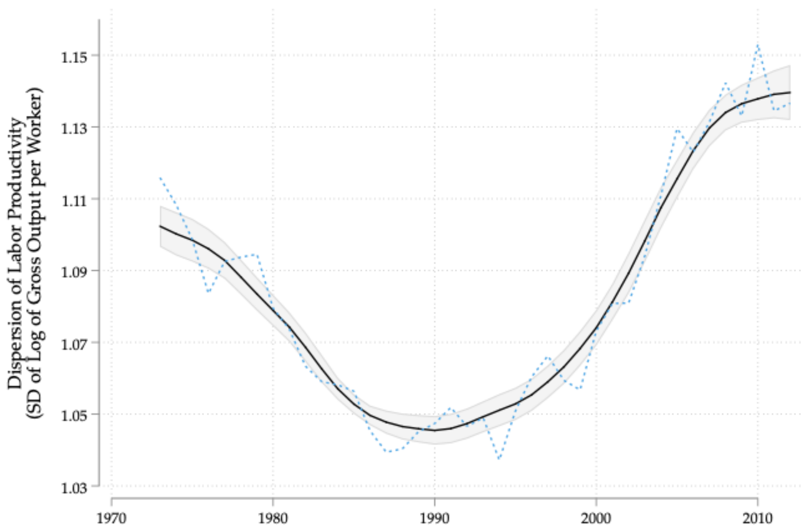

Figure 10: Sigma convergence and divergence.

Interestingly, the timing of the U-shaped pattern of labor productivity convergence/divergence matches closely with the Japanese asset price bubble's collapse of 1991 and its related economic stagnation of the 1990s and 2000s. Before the bubble's collapse, Japan achieved fast economic growth that allowed it to catch up with the most advanced economies of Europe and North America. Figure 10 provides some further insights about this catch-up process. Specifically, the fast economic growth of Japan appears to be associated with a reduction of labor productivity gaps across industries. After the bubble's collapse, however, overall economic growth in Japan stagnated. Moreover, the right-side of the U-shaped pattern of Figure 10, suggests that economic stagnation was accompanied with increasing productivity gaps across industries.

Consistent with the pattern of sigma convergence-divergence, Figure 11 also highlights the two distinct productivity eras of Japan by using the beta convergence approach. On the one hand, in the 1973–1990 period, the least productive industries have been catching up with the more productive ones. On the other, in the 1998–2012 period, this pattern is reversed. In other words, in more recent years, the least productive industries of Japan are not being able to catch up with the more productive ones.[19)]

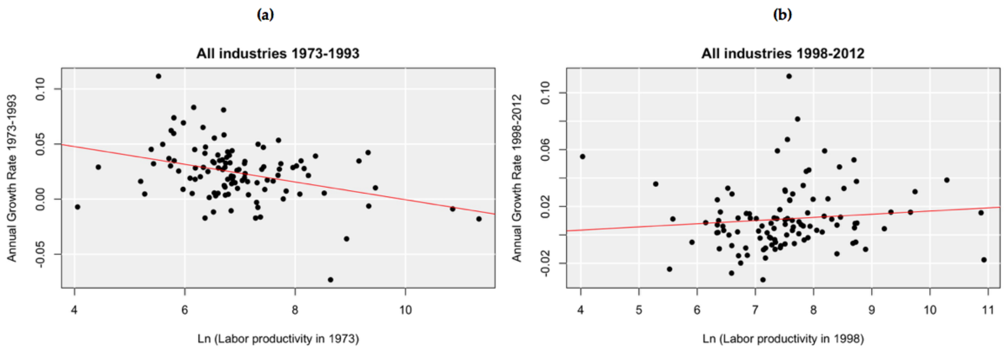

Figure 11: Beta convergence and divergence.

As previously noted, before its asset price bubble's collapse, Japan grew very fast and its industrial productivity gaps tended to decrease. In this context, panel (a) of Figure 11 shows that this decrease is explained in part by the faster productivity growth of the least productive industries. Among these industries,[20)] the ones that experienced the fastest growth rates between 1973 and 1993 were electronic data processing machines (11 percent), household electrical appliances (7 percent), and semiconductor devices and circuits (6 percent).

In contrast, after the bubble's collapse, Japan stagnated and its industrial productivity gaps tended to increase. In this context, Panel (b) of Figure 11 shows that the this increase is explained in part by the negative productivity growth of the least productive industries. Among these industries, the ones that experienced the largest negative growth rates are waste disposal services (−3.1 percent), private and non-profit education services (−2.6 percent), and private and non-profit hygiene services (−2.4 percent).

4. Results and Discussion

We first partition the network formed from the input-output data and get a community that is made of 44 out of 108 industries. The result of this partition can be seen in table 1 of the appendix. The formation of this group of industries can be explained because its members have strong connections among themselves, while having weaker connections with the rest of the economy. This is the idea of a community. This stationary community turns out to be composed by a large number of service-related industries.[21] Among them, finance and real estate (construction, finance, insurance, and so forth), transportation and related services (railway, road transportation; and the like) and health and welfare-related services (medical, hygiene, education). Since the remaining sectors of the economy were not present in the stationary community, we gathered them in the transitional community. These are shown in table 2 of the appendix. These results are similar to those proposed by the Melitz model (Melitz, 2003): the tradable goods sector tends to be more productive while the non-tradable one tends to be less productive.[22]

Figure 12 shows the structural differences of the two communities through the lens of both a standard centrality-and-dispersion analysis and the sigma convergence analysis. First, panel (a) and (b) present a simple analysis of centrality and dispersion similar to that of Figure 9. In terms of relative performance, the median labor productivity of the transitional community (panel b) has increased at a faster pace and, as a result, it ended up at a higher productivity level by the year 2012. These two panels also highlight the evolution of the productivity gaps within each community. Here again, the transitional community is particularly more interesting because the productivity gaps across industries (as measured by the interquartile range IQR) have drastically increased since the mid-1990s.

Panels (c) and (d) present the results of the partition through the lens of the sigma convergence approach. Both communities show a clear pattern of initial convergence (the dispersion decreases) followed by a period of divergence (the dispersion increases). The process of divergence in the transitional community (panel d), however, started earlier and appears to continue, although at a slower pace, in more recent years. In contrast, the stationary community appears to be starting a new wave of convergence since the year 2007.

Figure 13 shows the structural differences of the two communities through the lens of the beta convergence analysis. Similar to the sigma convergence results, both communities show a period of significant convergence followed by a period of lack of convergence. Furthermore, in the 1973–1993 period (panels a and c), the speed of beta convergence across industries in the stationary community is faster compared to that in the transitional community. In the 1993–2012 period, however, the slope of the regression lines (and the beta convergence coefficient) is not statistically different from zero in both communities.

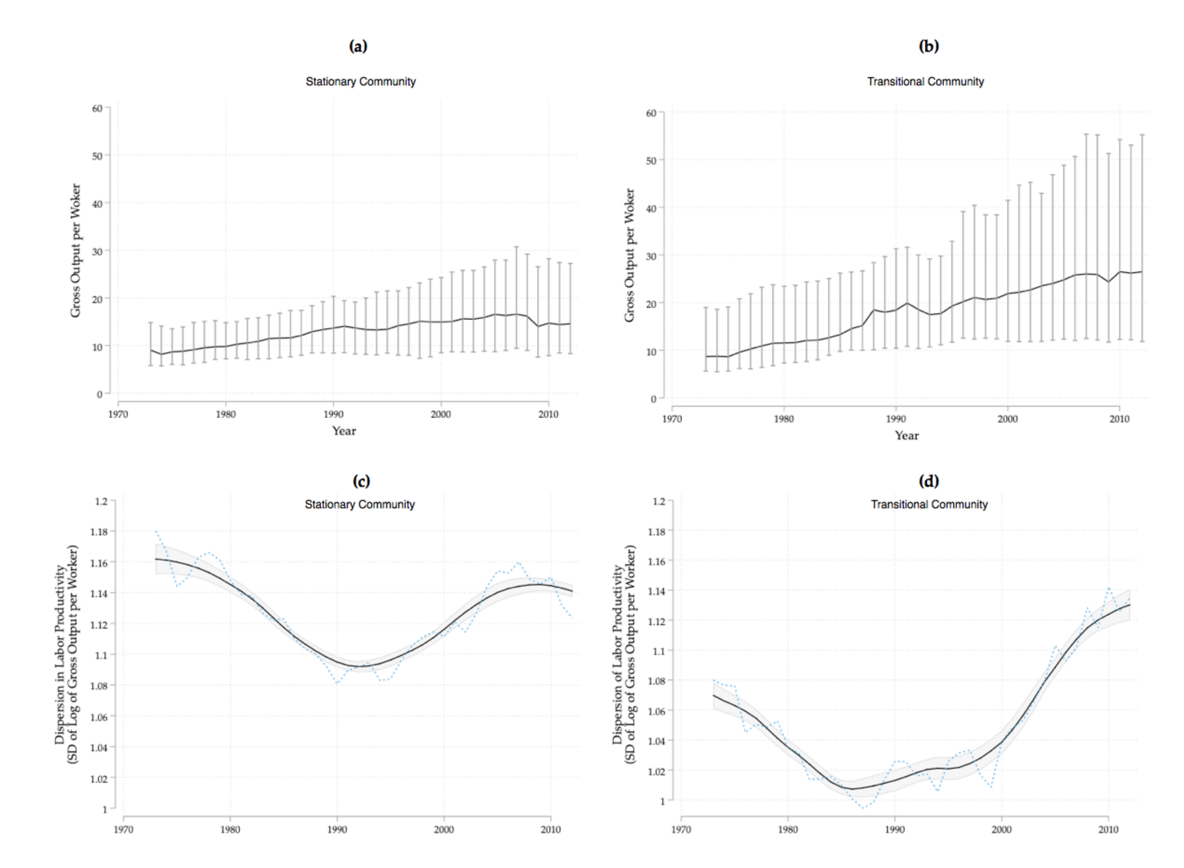

Figure 12: Sigma convergence approach: stationary and transitional communities.

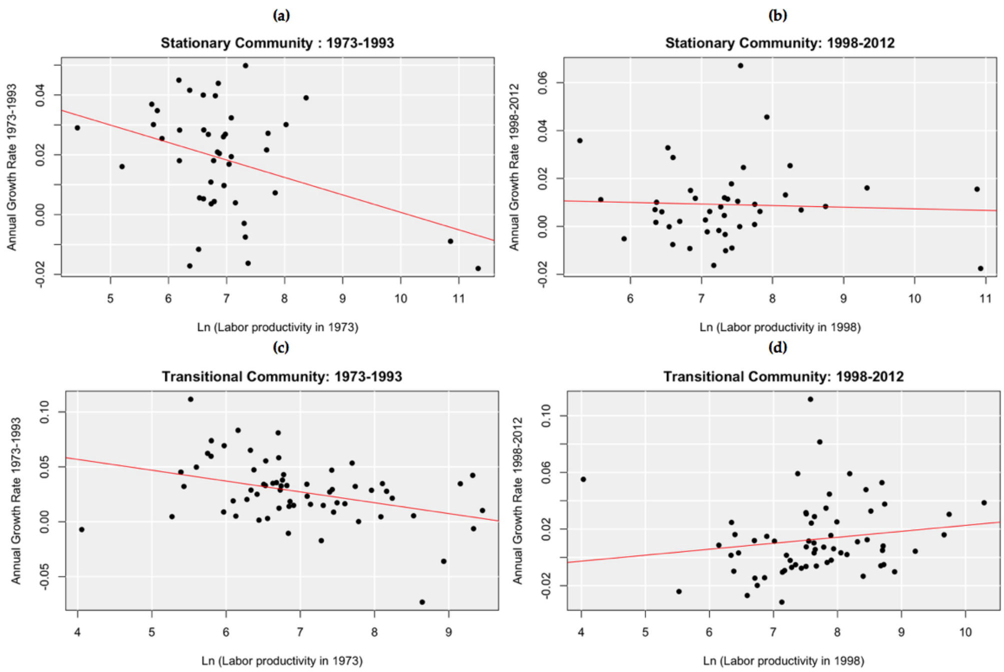

Figure 13: Beta convergence approach: stationary and transitional communities.

By focusing on the 1998–2012 sub-period, however, panels (b) and (d) of Figure 13 highlight an emerging difference between the two communities. If the slopes of the regression lines were to become statistically significant as new years are added to the analysis, then we could expect a significant pattern of beta convergence in the stationary community and a divergence pattern in the transitional community. These two processes, in turn, would reinforce the previously identified patterns of Figure 12, in which a new process of convergence may be appearing in the stationary community and a process of divergence may be continuing in the transitional community.

5. Conclusions

In this paper, we use input–output tables of Japan and analyze the productivity behavior of different community networks at the industry level. For this purpose, we implement the community detection algorithm of Newman (2006). Results from this analysis suggest the existence of two input-output network communities: a densely-connected group of industries (a stationary community), whose members remain in it throughout the period; and a group of industries (a transitional community) whose members do not belong to this first group. In terms of composition, the stationary community appears to be largely composed by service-related industries. Among them, finance and real estate, transportation and related services and health and welfare-related services.

Given these two kinds of network communities, we next evaluate to what extent the productivity of the members is converging. Results suggest that in more recent years, at least, industrial productivity divergence appears to be driven by the divergence patterns of the transitional community. Interestingly, since 2007, a pattern of convergence started to appear only in the stationary community. We also observe that productivity divergence and instability in community membership are not necessarily indicative of low economic performance. On average, divergent (and transitional) industries turn out to have a higher productivity level than their stationary counterparts. This finding could suggest that the members of the transitional community are diverging (or escaping) from a low-productivity equilibrium, while the members of the stationary community are converging towards one.

In the context of these findings, we could suggest at least two promising directions for further research. First, one could apply alternative community detection algorithms such as the Degree-corrected Stochastic Block Model (Karrer and Newman, 2011) and the Louvain Method (Blondel et al., 2008). Second, the convergence analysis could be based on frameworks that emphasize both technological heterogeneity and transitional modeling. Among them, the work of Phillips and Sul (2007a) and Phillips and Sul (2007b) may prove useful. By extending this kind of research in any of these directions, one could test whether these alternative techniques produce relatively similar or contrasting results.

6. Appendix

Table 2: Industries in the stationary community

JIP 2015		
No.	Industry No.	Industry name
1	1	Rice, wheat production
2	2	Miscellaneous crop farming
3	4	Agricultural services
4	5	Forestry
5	11	Miscellaneous foods and related products
6	13	Beverages
7	15	Textile products
8	18	Pulp, paper, and coated and glazed paper
9	19	Paper products
10	21	Leather and leather products
11	22	Rubber products
12	27	Chemical fibers
13	28	Miscellaneous chemical products
14	30	Petroleum products
15	35	Miscellaneous ceramic, stone and clay products
16	41	Miscellaneous fabricated metal products
17	57	Precision machinery and equipment
18	58	Plastic products
19	59	Miscellaneous manufacturing industries
20	60	Construction
21	62	Electricity
22	64	Waterworks
23	67	Wholesale
24	68	Retail
25	69	Finance
26	70	Insurance
27	71	Real estate
28	72	Housing
29	73	Railway
30	74	Road transportation
31	75	Water transportation
32	77	Other transportation and packing
33	86	Rental of office equipment and goods
34	87	Automobile maintenance services
35	88	Other services for businesses
36	89	Entertainment
37	98	Education (public)
38	100	Medical (public)
39	101	Hygiene (public)
40	102	Social insurance and social welfare (public)
41	104	Medical (non-profit)
42	105	Social insurance and social welfare (non-profit)
43	107	Others (non-profit)
44	108	Activities not elsewhere classified

Table 3: Industries in the transitional community

JIP 2015		
No.	Industry No.	Industry name
1	3	Livestock and sericulture farming
2	6	Fisheries
3	7	Mining
4	8	Livestock products
5	9	Seafood products
6	10	Flour and grain mill products
7	12	Prepared animal foods and organic fertilizers
8	14	Tobacco
9	16	Lumber and wood products
10	17	Furniture and fixtures
11	20	Printing, plate making for printing and bookbinding
12	23	Chemical fertilizers
13	24	Basic inorganic chemicals
14	25	Basic organic chemicals
15	26	Organic chemicals
16	29	Pharmaceutical products
17	31	Coal products
18	32	Glass and its products
19	33	Cement and its products
20	34	Pottery
21	36	Pig iron and crude steel
22	37	Miscellaneous iron and steel
23	38	Smelting and refining of non-ferrous metals
24	39	Non-ferrous metal products
25	40	Fabricated constructional and architectural metal products
26	42	General industry machinery
27	43	Special industry machinery
28	44	Miscellaneous machinery
29	45	Office and service industry machines
30	46	Electrical generating, transmission, distribution and industrial apparatus
31	47	Household electric appliances
32	48	Electronic data processing machines, digital and analog computer equipment and accessories

33	49	Communication equipment
34	50	Electronic equipment and electric measuring instruments
35	51	Semiconductor devices and integrated circuits
36	52	Electronic parts
37	53	Miscellaneous electrical machinery equipment
38	54	Motor vehicles
39	55	Motor vehicle parts and accessories
40	56	Other transportation equipment
41	61	Civil engineering
42	63	Gas, heat supply
43	65	Water supply for industrial use
44	66	Waste disposal
45	76	Air transportation
46	78	Telegraph and telephone
47	79	Mail
48	80	Education (private and non-profit)
49	81	Research (private)
50	82	Medical (private)
51	83	Hygiene (private and non-profit)
52	84	Other public services
53	85	Advertising
54	90	Broadcasting
55	91	Information services and internet-based services
56	92	Publishing
57	93	Video picture, sound information, character information production and distribution
58	94	Eating and drinking places
59	95	Accommodation
60	96	Laundry, beauty and bath services
61	97	Other services for individuals
62	99	Research (public)
63	103	Public administration
64	106	Research (non-profit)

IV. Strategic Formation of Bargaining Networks with Heterogeneous Costs

Abstract

We present a model analyzing the endogenous network formation prior to an infinite-horizon network bargaining game. We assume agents of two types with connections among players of the same type being cheaper than among players of different types. In this way, players not only need to consider the trade-off between more outside options and the costs of maintaining those additional links, but also what type of players they connect to. We characterize pairwise stable network structures through sufficient conditions, highlighting the role played by the way in which heterogeneous nodes are placed in the different components for the pairwise stability of the networks.

Keywords: Bargaining, Network formation, Heterogeneity.

1. Introduction

Network structures are used to model situations in which only pairs of connected agents may engage in exchange. It is easy to see that for example trading opportunities that depend on social relationships fit in this category. Moreover, sometimes it is reasonable to assume that the cost to sustain these social relationships depends on the characteristics of the connected individuals: it is easier to trade with people who speak the same language, and it is also easier to trade products between countries with harmonized regulations.

When networks representing bargaining opportunities are not exogenously given but endogenously determined, Gauer and Hellmann (2017) explain the trade-off faced by the agents when forming a new link: new connections affect the bargaining power because they increase the number of outside options but, on the flip side, they are costly to form and maintain. In our framework, we add one more layer: the cost of the link depends on the types of the connected players. Therefore, whether two players of different type will connect is determined by the entire network structure.

We study the endogenous network formation prior to a Manea (2011) infinite-horizon network bargaining game, assuming that there are agents of two types and that connections among players of the same type are cheaper than among players of different types. The sufficient conditions characterizing the equilibrium network structures rely on the notion of pairwise stability introduced by Jackson and Wolinsky (1996). We find that, as in Gauer and Hellmann (2017), the stable components are isolated nodes, pairs, lines of length three, and odd cycles. However, our framework allows us to highlight the role played by the way in which the heterogeneous nodes are placed in the different components for the pairwise stability of the network.

The rest of the paper is organized as follows: Section 2 describes the model. Section 3 provides the sufficient conditions for pairwise stable components and networks, emphasizing that only certain heterogeneous configurations can happen in equilibrium. Section 4 concludes, and the mathematical proofs are presented in Appendix A.

(1). Literature Review

Our paper contributes to the literature of bargaining in networks. The study of bargaining has a long history starting with the seminal papers by Nash (1950), Nash (1953) and Rubinstein (1982). While the former follows an axiomatic approach, the latter attempts to look into the bargaining black-box, proposing a strategic model of alternating offers between two players whose results converge to those obtained by Nash when the players are infinitely patient.

Rubinstein and Wolinsky (1985) provide further insights into the process of decentralized bargaining in stationary markets, which would later allow for the study of bargaining in stationary networks. The authors assume that after a buyer and a seller reach an agreement they leave the market, and that this flow of departure is matched by an equal arrival flow of new agents of both types. But whereas in stationary networks the bargaining power is determined by the relative position of the nodes, when a network is not considered the driving force is the difference in the relative sizes of the two market sides.

The contributions to the literature of bargaining in exogenously-determined networks can be divided in two groups: those assuming stationary networks and those assuming non-stationary networks.

Stationary networks are those in which players reaching an agreement leave the market but are replaced by identical players in the subsequent period, and so the network structure remains the same.

Manea (2011) studies an infinite-horizon bargaining game in a stationary, undirected network. Although, contrary to our approach, the author considers the network structure as given, he shows that not all existing links will be used when players are patient enough; that is, there are pairs of players that, when selected to bargain, do not reach an agreement and instead prefer to wait to be matched with another trading partner. We make use of the algorithm developed in this paper to compute the equilibrium payoffs of the players when they are patient enough.

Gauer and Hellmann (2017) extend the model of Manea (2011) by considering the endogenous network formation in a stage prior to stationary bargaining. In their setup, players are ex ante homogeneous and to sustain the (undirected) links is costly. We generalize their framework by assuming that there can be two different types of players, such that links between players of the same type are cheaper to create and maintain than those between players of different types.

Non-stationary networks are those in which the players reaching an agreement leave the market but they are not replaced. Their links in the network are also removed, so the network structure changes every time after an agreement.

Corominas-Bosch (2004) and Polanski (2007) study how centralized bargaining in networks work, with the latter generalizing the framework of the former by not limiting attention to bipartite graphs. Abreu and Manea (2012a) and Abreu and Manea (2012b) examine a model similar to Polanski (2007) but for decentralized bargaining, in which not all matchings necessarily lead to agreements and where multiple equilibria may exist.

2. The model

Assume a set of players $N = \{1,2,...n\}$ with $n \geq 3$ for a time period $t = 0,1,2,...$ in which players interact. In the first period, $t = 0$, players form links in the network and from periods $t = 1,2,...$ they perform an infinite horizon bargaining game to split the unit surplus created from the links.

Denote a link between players $i, j \in N, i \neq j$ as $ij = ji = \{i, j\}$. Let g^N be the complete network, that is, the set of all subsets of N of size 2. Then the set of all networks that are undirected is $G = \{g \mid g \subseteq g^N\}$. We define the neighbors of player i as $N_i(g) = \{j \in N \mid ij \in N\}$ and let $\eta_i(g) = |N_i(g)|$ denote player i's *degree* (i.e. the cardinality of i's neighbors). Given a network g, a *path* between players i and j is a sequence of players $i_1, i_2, ..., i_M$ such that $i_m i_{m+1} \in g$ for all $m \in \{1,...M-1\}$, with $i_1 = i$ and $i_M = j$. Let $C \subseteq N$ be a *component* of network g and we say that players $i, j \in C$ if there is a path between them in C, with $N_j(g) \cap C = \varnothing$ for all $j \neq C$. We say that a *subnetwork* $g' \subseteq g$ is *component-induced* if there is a component C of g such that $g' | g_C$ where the network defined as $g|_K = \{ij \in g \mid i, j \in K\}$ is the subnetwork limited to the players $K \subset N$. Given the networks $g, g' \subseteq g^N$, let $g + g' = g \cup g'$ represent the network obtained from adding the links $g' \setminus g$. Likewise, let $g - g' = g \setminus g'$ be the network obtained from severing links $g' \cap g$ from network g.

After the network formation stage, which happens at $t = 0$, bargaining takes place. This stage is modeled following Manea (2011): in periods $t = 1,2,...$, the uniform matching technology is assumed, which means that any link $ij \in g$ is randomly selected with probability p. Then, again with equal probability, one of the two players involved is selected as the proposer while the other is the responder. From the link that is selected, both players bargain about the surplus that is produced. The proposer makes an offer specifying how to divide the unit surplus from the link, while the responder either accepts it or rejects it. If the offer is rejected, both parties obtain zero as a payoff and continue in the game. If the offer is accepted, then both parties leave the game with the allocation that they agreed upon and they are replaced by new identical players at the exact same position, so that the network structure is not altered. All offers, responses and the network structure are considered to be common knowledge. It is important to note that players' payoffs are given by the discounted expected agreement share. In this game, players discount time by the discount factor $\delta \in (0,1)$. Additionally, we say that a strategy profile is a sub-game perfect equilibrium of the game if it induces Nash equilibria in subgames following every history.

Manea (2011) finds that all sub-game perfect equilibria has an identical payoff. Furthermore, the payoff equilibrium for each player will depend only on that player's position in the network along with the discount factor δ. The unique solution to the equation system

$$v_i = \left(1 - \sum_{j \in N_i(g)} \frac{p}{2}\right) \delta v_i + \sum_{j \in N_i(g)} \frac{p}{2} \max\left(1 - \delta v_j, \delta v_i\right) \tag{9}$$

will be given by the *equilibrium payoff vector*, expressed by $v^{*\delta}(g) = \left(v_i^{*\delta}(g)\right)_{i \in N}$. Equation (1) must be satisfied by the equilibrium payoff because, by the stationarity assumption, strategies have to be such that a sub-game perfect equilibrium exists in which a given player i will always accept any offer for which he can obtain at least his continuation payoff, δv_i, and will always make the same proposals for identical responders. By offering δv_j to player j, player i will obtain $1 - \delta v_j$, which should not be less than his continuation payoff. Player i proposes to player j with probability $p/2$; that is, the probability of being chosen from all players in the network. From this we see that equilibrium payoffs have to satisfy (1) and are the unique solution to it; in other words, the solution is the unique fixed point. Thus, any equilibrium agreement between i and j is attainable if $\delta\left(v_i^{*\delta}(g) + v_j^{*\delta}(g)\right) \leq 1$ from which an *equilibrium agreement network* is defined as $g^{*\delta} = \left\{ij \in g \mid \delta_i^{*\delta}(g) + v_j^{*\delta}(g)\right\} \leq 1$.

We focus on the case when $\delta \to 1$, which means that players tend to be infinitely patient. In this way, equilibrium payoffs depend exclusively on the network structure. For large enough discount factors, Manea (2011) finds that the limit equilibrium agreement network does not change when δ does once g

has been formed in the first stage; furthermore, the limit equilibrium payoff vector $v^*(g) = \lim_{\delta \to 1} v^{*\delta}(g)$ always exists.

We make use of the algorithm developed by Manea (2011) to compute the limit equilibrium payoff vector. Given a player set $M \subseteq N$ and a network g, the partner set in g is defined as $L^g(M) = \{j \in N | ij \in g, i \in M\}$. Finally, we say that a set $M \subseteq N$ is *g-independent* if no pair of players in M are connected in the network g. With these elements, the algorithm is defined as follows:

Definition 1 (Manea, 2011)**.** *For a given network g and player set N, the algorithm $\mathscr{A}(g)$ provides a sequence $(r_s, x_s, M_s, L_s, N_s, g_s)_{s=1,2,\ldots,\bar{s}}$ which is defined recursively as follows. Let $N_1 = N$ and $g_1 = g$. For $s \geq 1$, if $N_s = \varnothing$ then stop and set $\bar{s} = s$. Otherwise let*

$$r_s = \min_{M \subseteq N, M \in \mathscr{I}(g)} \frac{|L^{g_s}(M)|}{|M|}, \tag{10}$$

with $\mathscr{I}(g)$ denoting the set of nonempty g-independent sets.

If $r_s \geq 1$ then stop and set $\bar{s} = s$. Otherwise, set $x_s = r_s/(1+r_s)$. Let M_s be the union of all minimizers in (10). Define $L_s = L^{g_s}(M_s)$. Let $N_{s+1} = N_s \setminus (M_s \cup L_s)$ and g_{s+1} be the subnetwork of g induced by players in N_{s+1}.

Let the result of $\mathscr{A}(g)$ be given by the sequence $(r_s, x_s, M_s, L_s, N_s, g_s)_{s=1,2,\ldots,\bar{s}}$. We say that the limit equilibrium payoffs are then given by:

$$\begin{aligned}
v_i^* &= x_s, \forall i \in M_s, \forall s < \bar{s} \\
v_j^* &= 1 - x_s, \forall j \in L_s, \forall s < \bar{s} \\
v_k^* &= \frac{1}{2}, \forall k \in N_{\bar{s}}
\end{aligned}$$

At each step s the algorithm $\mathscr{A}(g)$ searches for the *minimal shortage ratio* r_s from N_s (the remaining players N after each step) in the network $g_s = g|_{N_s}$, resulting from the largest g_s-independent set M_s to minimize $r_s = |L_s| / |M_s|$, with L_s representing the partner set of M_s. The smaller the composition of L_s relative to M_s is, the stronger the bargaining power that its members have to obtain bigger shares of the produced surplus. Relying on the algorithm, we can then find at each step the minimal shortage ratio and detect the players with the best and worst bargaining positions. The limit equilibrium payoffs for the players in M_s is given by $x_s = |L_s| / |L_s + M_s| = r_s/(1+r_s)$ and for those in L_s is $1 - x_s = |M_s| / |L_s + M_s| =$

$1/(1+r_s)$. It is easy to see that x_s is increasing in the shortage ratio. After each step, the matched players are removed from the game and the algorithm continues onward to the next step. This process continues until there are no more players left to match in the game or until $r_s \geq 1$. For this latter case, each of the remaining players receives the payoff $1/2$.

During the first stage, when the network is being formed, players foresee their payoffs from the bargaining game. We consider that there are two different types of players. Maintaining each link formed imposes a strictly positive cost to each of the players involved: this cost is low when the link connects two players of the same type, and high otherwise. At $t = 0$, each player tries to maximize their profit, expressed as

$$u_i^*(g) := v_i^*(g) - \overline{\eta}_i(g)\overline{c} - \underline{\eta}_i(g)\underline{c},$$

where $\overline{\eta}_i(g)$ represents the cardinality of the players of different type than i that are his neighbors, and $\underline{\eta}_i(g)$ denotes the cardinality of the players of the same type as i who are his neighbors.

Whether a link is created or not is determined by the resolution of the following trade-off: on the one hand, a link may benefit the involved players by altering their relative positions (and gross payoffs) in the network; on the other hand, a link is costly and this cost depends on the type of the connected players.

Following Gauer and Hellmann (2017), the profit profile $u^* = (u_i^*)_{i\in N}$ is said to be *component-decomposable* since $u_i^*(g) = u_i^*(g|_{C_{i(g)}})$ $\forall i \in N$ and g. $C_i \subseteq N$ represents the component of player i in network g, and we see that subnetworks induced by other components will not modify player i's profits as long as he does not belong to them.[23)] As they did, we also rely on the equilibrium notion of Pairwise Stability and do not explicitly model the network formation in stage $t = 0$:

Definition 2 (Jackson and Wolinsky, 1996)**.** *A network g is pairwise stable if:*

1. *for all $ij \in g : u_i(g) \geq u_i(g - ij)$ and $u_j(g) \geq u_j(g - ij)$, and*
2. *for all $ij \notin g$: if $u_i(g + ij) > u_i(g)$, then $u_j(g + ij) < u_j(g)$*

The first part of the definition requires that no player wishes to delete a link that they are involved in; the second part requires that if some link is not in the network and one of the involved players would benefit from adding it, then it must be that the other player would suffer from the addition of the link. In other words, for a network to be pairwise stable, all players must desire to retain their existing links and no given pair of players wish to form a new one between themselves.

3. Results

In this section we present sufficient conditions for pairwise stability. The two lemmas deal with the stability of individual components, whereas the three theorems characterize pairwise-stable networks with more than one component.

(1). Lemmas

Lemma 1. *Sufficient conditions for components to be pairwise stable:*

(i) The homogeneous pair [24] *is pairwise stable if* $\underline{c} \leq \frac{1}{2} \wedge \overline{c} > \underline{c}$.

The heterogeneous pair [25] *is pairwise stable if* $\underline{c} < \overline{c} \leq \frac{1}{2}$.

(ii) The homogeneous line of length three [26] *is pairwise stable if* $\frac{1}{6} = \underline{c} < \overline{c}$.

The heterogeneous line of length three such that two nodes of the same type are consecutive [27] *is pairwise stable if* $\underline{c} < \overline{c} = \frac{1}{6}$.

(iii) The homogeneous odd cycle [28] *with at most* $\frac{1}{2\underline{c}}$ *players is pairwise stable if* $\underline{c} \leq \frac{1}{6} \wedge \overline{c} > \underline{c}$.

The heterogeneous odd cycle [29] *with at most* $\frac{1}{2\overline{c}}$ *players is pairwise stable if* $\underline{c} < \overline{c} \leq \frac{1}{6}$.

Proof.

In the Appendix. □

Lemma 2. *The following components are not pairwise stable:*

(i) Heterogeneous lines of length three such that two nodes of the same type are not consecutive.

(ii) Lines of length four or above.

(iii) Even cycles.

Proof.

In the Appendix. □

These results include those in Gauer and Hellmann (2017) as particular cases. There are two results worth a comment: the heterogeneous lines of length three, and the heterogeneous odd cycles.

Notice that, for heterogeneous lines of length three to be pairwise stable, it must be that the two nodes of the same type are consecutive. The intuition for this result is as follows: if the two nodes of the same type are not consecutive, the two existing links are expensive, which requires $\overline{c} \leq 1/6$. However, being of the same type, for the two peripheral nodes it is profitable to connect themselves if $\underline{c} \leq 1/6$, which is automatically implied by the previous condition; that is, in a line of length three, it is not possible to sustain two expensive links while preventing a cheap one.

On the other hand, when the two nodes of the same type are consecutive in the line of length three, there are a cheap link and an expensive link. Since the two peripheral nodes are different, the structure is stable if $\overline{c} = 1/6$, because that is the limiting value to simultaneously sustain the existing expensive link and prevent the formation of the cycle by adding an expensive link. Also, since the expensive link is maintained, so is the cheap existing one.

With respect to the heterogeneous odd cycles, the pairwise-stability condition is the same regardless of the number of nodes of each type and their positions in the cycle: since the cycle is odd, it is not profitable to add any link and so the only concern is to sustain the existing ones. In this structure, any pair of players involved in a link break would see themselves at the extremes of an odd line, and this symmetry explains why sustaining one expensive link in the cycle is not less demanding than sustaining more than one expensive link.

(2). Theorems

Theorem 3 (Pairwise stability of the empty network)**.**
The empty network is pairwise stable if $\underline{c} \geq \frac{1}{2}$.

Proof.
In the Appendix. □

This result coincides with Gauer and Hellmann (2017): whereas in our setup the empty network may include nodes of different types, preventing the formation of a cheap link automatically prevents the formation of an expensive link, and so the relevant cost is $\underline{c}$ only.

Theorem 4 (Pairwise stable networks including only pairs and isolated nodes)**.**

(i) Networks consisting of the union of one isolated node and homogeneous pairs such that at least one is of the same type as the isolated, are pairwise stable if $\frac{1}{6} < \underline{c} \leq \frac{1}{2} \wedge \overline{c} > \underline{c}$.

(ii) *Networks consisting of the union of one isolated player and homogeneous pairs such that all are of the same type and different from the isolated, are pairwise stable if* $\underline{c} \leq \frac{1}{2} \wedge \overline{c} > \max\left\{\frac{1}{6}, \underline{c}\right\}$.

(iii) *Networks consisting of the union of homogeneous pairs, regardless of their types, and two isolated nodes such that each one of them is of a different type are pairwise stable if* $\frac{1}{6} < \underline{c} \leq \frac{1}{2} \leq \overline{c} \wedge \overline{c} > \underline{c}$. *Additionally, if* $\underline{c} = \frac{1}{2}$, *then there can exist two isolated nodes of the same type or three or more isolated nodes of any type.*

(iv) *Networks consisting of the union of pairs such that at least one is heterogeneous and one isolated node are pairwise stable if* $\frac{1}{6} < \underline{c} < \overline{c} \leq \frac{1}{2}$. *Additionally, if* $\frac{1}{6} < \underline{c} < \overline{c} = \frac{1}{2}$, *then there can exist two isolated nodes such that each one of them is of a different type.*

Proof.
In the Appendix. □

The first statement of Theorem 2 contains the result in Gauer and Hellmann (2017) as a particular case, while it also allows for the existence of homogeneous pairs different from the isolated player. However, in the second statement all pairs are homogeneous and different from the isolated node, which is reflected in the stability condition: to prevent the link between an isolated node and a pair of the same type, $1/6 < \underline{c}$ is sufficient, whereas to prevent the link between an isolated node and a pair of different type, the sufficient condition becomes $1/6 < \overline{c}$.

An important difference with Gauer and Hellmann (2017) is that there can be two isolated nodes rather than one in a network with only homogeneous pairs for different values of the costs within certain intervals. Of course, this happens because the condition to sustain the homogeneous pairs depends on $\underline{c}$ and the condition to prevent the link between the two isolated nodes that are of different types depends on $\overline{c}$. However, to allow for the existence of two or more isolated nodes of the same type, we need to fix the cheap cost at the particular limiting value $1/2$.

Finally, it is also possible to sustain heterogeneous pairs with one isolated node for different values of the costs within certain intervals. Nonetheless, in order to allow for two isolated nodes of different types to exist in this structure, the expensive cost needs to take the particular limiting value $1/2$. Notice that it is impossible to allow for three or more isolated nodes while sustaining heterogeneous pairs, because in that case it would be impossible to prevent the link between two isolated nodes of the same type.

Theorem 5 (Pairwise stable networks that include cycles)**.**

(i) Networks consisting of the union of homogeneous odd cycles, regardless of their types, with at most $\frac{1}{2\underline{c}}$ *players, and two isolated nodes, one of each type, are pairwise stable if* $\underline{c} \leq \frac{1}{6} \wedge \overline{c} \geq \frac{1}{2}$.

(ii) Networks consisting of the union of homogeneous cycles, regardless of their types, with at most $\frac{1}{2\underline{c}}$ *players, and either homogeneous pairs, regardless of their types, or at most one isolated player are pairwise stable if* $\underline{c} \leq \frac{1}{6} \wedge \overline{c} > \underline{c}$. *Additionally, if* $\underline{c} = \frac{1}{6}$ *and given that there is no isolated player, then there can also be homogeneous lines of length three, regardless of their types.*

(iii) Networks consisting of the union of homogeneous cycles, regardless of their types, with at most $\frac{1}{2\underline{c}}$ *players, and pairs such that at least one of them is heterogeneous are pairwise stable if* $\underline{c} \leq \frac{1}{6} \wedge \underline{c} < \overline{c} \leq \frac{1}{2}$. *Additionally, if* $\underline{c} = \frac{1}{6}$, *then there can also be homogeneous lines of length three, regardless of their types.*

(iv) Networks consisting of the union of homogeneous odd cycles, regardless of their types, with at most $\frac{1}{2\underline{c}}$ *players, one isolated player and homogeneous pairs such that all are of the same type and different from the isolated node are pairwise stable if* $\underline{c} \leq \frac{1}{6} < \overline{c}$. *Additionally, if* $\underline{c} = \frac{1}{6}$, *then there can also be homogeneous lines of length three such that all are of the same type and different from the isolated node.*

(v) Networks consisting of the union of odd cycles such that at least one is heterogeneous, with at most $\frac{1}{2\underline{c}}$ *players in the homogeneous cycle(s) and at most* $\frac{1}{2\overline{c}}$ *players in the heterogeneous cycle(s), and either pairs or at most one isolated player are pairwise stable if* $\underline{c} < \overline{c} \leq \frac{1}{6}$.

(vi) Networks consisting of the union of odd cycles, with at most $\frac{1}{2\underline{c}}$ *players in the homogeneous cycle(s) and 3 players in the heterogeneous cycle(s), and one heterogeneous line of length three are pairwise stable if* $\underline{c} < \overline{c} = \frac{1}{6}$. *Additionally, if* $\frac{1}{15} < \underline{c}$, *then there can also be pairs.*

Proof.

In the Appendix. □

Notice that the first statement of Theorem 3 cannot be obtained in Gauer and Hellmann (2017), because if a homogeneous odd cycle is sustainable, then the two isolated nodes of the same type will form a pair. However, if the isolated nodes are of different types, the sufficient condition to sustain the homogeneous odd cycle depends on $\underline{c}$ whereas the sufficient condition to prevent the formation of a heterogeneous pair depends on $\overline{c}$.

The second statement of Theorem 3 includes the results in Gauer and Hellmann (2017) as a particular case, while it is not restricted to structures in which all pairs and cycles are of the same type (just being homogeneous is enough).

The lines of length three deserve further attention, as their existence in the pairwise stable network structures limits the characteristics of the other components. In particular, homogeneous lines can coexist with isolated nodes of different type, pairs, other homogeneous lines and homogeneous cycles with three players, but not with heterogeneous cycles. On the other hand, heterogeneous lines cannot coexist with other lines or isolated players, but they can with pairs and cycles. Moreover, they limit the number of players in the heterogeneous cycles to three, but they do not limit the number of players in the homogeneous cycles.

Finally, it is important to remark that there are multiple equilibria for certain parametric conditions. For example, if $\underline{c} \leq 1/6 \wedge 1/6 < \overline{c} \leq 1/2$, a network structure with the characteristics defined in Theorem 2 *(ii)* is pairwise stable, and so is a network structure with the characteristics defined in Theorem 3 *(iii)*. Our results simply state that the two configurations are pairwise stable, but nothing is said about which configuration would be finally reached, or with which probability.

4. Conclusions

We have presented a model to analyze the endogenous network formation prior to a Manea (2011) infinite-horizon network bargaining game, assuming that there are agents of two types and that connections among players of the same type are cheaper than among players of different types. This consideration added one more layer to the basic trade-off pointed out by Gauer and Hellmann (2017): additional links provide more outside options but they are costly, and this cost depends on the characteristics of the agents involved in the formation of the link.

Key results regarding the pairwise stability of components refer to heterogeneous lines of length three and heterogeneous odd cycles. While for heterogeneous lines of length three to be pairwise stable it must be that the two nodes of the same type are consecutive, for heterogeneous odd cycles to be pairwise stable it does not matter either how many nodes of each type there are or their positions in the cycle.

Key results regarding the pairwise stability of network structures refer to the components that can co-exist. Whereas pairs and cycles, both homogeneous and heterogeneous, co-exist in many configurations, the existence of lines of length three imposes further constraints. In particular, homogeneous lines can co-exist with isolated nodes of different type, pairs, other homogeneous lines and homogeneous cycles with three players, but not with heterogeneous cycles. On the other hand, heterogeneous lines cannot co-exist with other lines or isolated players, but they can with pairs and cycles. Moreover, they limit the number of players in the heterogeneous cycles to three, but they do not limit the number of players in the homogeneous cycles.

Although in this paper we have considered just two different types of agents, it would be interesting to extend the model to r types of agents and c_1, c_2, ..., c_r different linking costs. This consideration is left for future research.

5. Appendix

Proof. Lemma 1:

(i) Pairs: according to the definition of Pairwise Stability, we only need to find the condition for the existing link to be kept.

Homogeneous: the cost for each player to sustain the link is $\underline{c}$. When broken, they become isolated and get 0. Then, $1/2-\underline{c} \geq 0 \Leftrightarrow \underline{c} \leq 1/2$. Therefore, the homogeneous pair is pairwise stable if $\underline{c} \leq \frac{1}{2} \wedge \overline{c} > \underline{c}$.

Heterogeneous: the cost for each player to sustain the link is $\overline{c}$. When broken, they become isolated ad get 0. Then, $1/2-\overline{c} \geq 0 \Leftrightarrow \overline{c} \leq 1/2$. Therefore, the heterogeneous pair is pairwise stable if $\underline{c} < \overline{c} \leq \frac{1}{2}$.

(ii) Lines of length three: according to the definition of Pairwise Stability, we need to check that the two links connecting each peripheral player with the central node are kept, and that the peripheral players do not want to create a link among themselves.

Homogeneous: the cost for each player to sustain a link is $\underline{c}$. When broken, the central node becomes part of a pair, receiving the gross payoff $1/2$, and the peripheral node becomes isolated, getting 0. Then, for the link to be sustained:

- central node: $\frac{2}{3}-2\underline{c} \geq \frac{1}{2}-\underline{c} \Leftrightarrow \underline{c} \leq \frac{1}{6}$.

- peripheral node: $\frac{1}{3} - \underline{c} \geq 0 \Leftrightarrow \underline{c} \leq \frac{1}{3}$.

Thus, the link is sustained if $\underline{c} \leq 1/6$.

The cost for each peripheral player to form a new link is $\underline{c}$. Then, as the payoffs are the same for both peripheral nodes,

- create if $\frac{1}{2} - 2\underline{c} > \frac{1}{3} - \underline{c} \Leftrightarrow \underline{c} < \frac{1}{6}$.

Thus, the link is not created if $\underline{c} \geq 1/6$.

Therefore, the homogeneous line of length three is pairwise stable if $\frac{1}{6} = \underline{c} < \overline{c}$.

Heterogeneous: the cost for players of the same type to sustain a link is $\underline{c}$, while for players of different types it is $\overline{c}$. When broken, the central node becomes part of a pair, receiving the gross payoff $1/2$, and the peripheral node becomes isolated, getting 0. Then,

- central node with peripheral node of the same type:
  - central node: $\frac{2}{3} - \overline{c} - \underline{c} \geq \frac{1}{2} - \overline{c} \Leftrightarrow \underline{c} \leq \frac{1}{6}$.
  - peripheral node: $\frac{1}{3} - \underline{c} \geq 0 \Leftrightarrow \underline{c} \leq \frac{1}{3}$.

  The link is sustained if $\underline{c} \leq 1/6$.

- central node with peripheral node of different type:
  - central node: $\frac{2}{3} - \overline{c} - \underline{c} \geq \frac{1}{2} - \underline{c} \Leftrightarrow \overline{c} \leq \frac{1}{6}$.
  - peripheral node: $\frac{1}{3} - \overline{c} \geq 0 \Leftrightarrow \overline{c} \leq \frac{1}{3}$.

  The link is sustained if $\overline{c} \leq 1/6$.

The cost for each peripheral player to form a new link is $\overline{c}$, in which case an odd cycle is created and each player receives the gross payoff $1/2$. Then, as the payoffs are the same for both peripheral nodes,

- create if $\frac{1}{2} - c_i^N - \overline{c} > \frac{1}{3} - c_i^N - \Leftrightarrow \overline{c} < \frac{1}{6}$,

  where $c_i^N = \{\overline{c}, \underline{c}\}$ represents the cost for each peripheral player i to be connected to the neighbor they are not considering to break with (which is the central node in this case).

Thus, the link is not created if $\overline{c} \geq 1/6$.

Therefore, the heterogeneous line of length three such that two nodes of the same type are consecutive is pairwise stable if $\underline{c} < \overline{c} = \frac{1}{6}$.

(iii) odd cycles: according to the definition of Pairwise Stability, we need to find the conditions for each node to keep the links with its two neighbors, and for no additional link to be created.

Homogeneous: the cost for each player to sustain a link is $\underline{c}$. If the link is broken, each node ends up at one of the extremes of an odd line of length $\underline{m}$, receiving the gross payoff $(\underline{m}-1)/2\underline{m}$. Then,

$$\frac{1}{2} - \underline{c} - \underline{c} \geq \frac{\underline{m}-1}{2\underline{m}} - \underline{c} \Leftrightarrow \underline{c} \leq \frac{1}{2\underline{m}}$$

As $\underline{m} \geq 3$, $\underline{c} \leq \frac{1}{6}$.

Notice that, after creating a link between two nodes of the cycle that were unconnected, the gross payoff for each player remains $\frac{1}{2}$, as the cycle is odd. Then, these players were strictly better off without the additional link for any $\underline{c} > 0$.

Therefore, the homogeneous odd cycle with at most $\frac{1}{2\underline{c}}$ players is pairwise stable if $\underline{c} \leq \frac{1}{6} \wedge \overline{c} > \underline{c}$.

Heterogeneous: the cost for players of the same type to sustain a link is $\underline{c}$, while for players of different types it is $\overline{c}$. If the link is broken, each node ends up at one of the extremes of an odd line of length $\overline{m}$, receiving the gross payoff $(\overline{m}-1)/2\overline{m}$. Sustaining links between players of different types automatically guarantees that links between players of the same type are sustained as well. Also, notice that in heterogeneous odd cycles there is always at least one link that costs $\overline{c}$ for the players involved. Then,

$$\frac{1}{2} - c_i^N - \overline{c} \geq \frac{\overline{m}-1}{2\overline{m}} - c_i^N \Leftrightarrow \overline{c} \leq \frac{1}{2\overline{m}}$$

where $c_i^N = \{\overline{c}, \underline{c}\}$ represents the cost for each node i to be connected to the neighbor they are not considering to break with.

As $\overline{m} \geq 3$, $\overline{c} \leq \frac{1}{6}$.

Again, after creating a link between two nodes of the cycle that were unconnected, the gross payoff for each player remains $\frac{1}{2}$, as the cycle is odd. Then, these players were strictly better off without the additional link for any $\underline{c} > 0$.

Therefore, the heterogeneous cycle with at most $\frac{1}{2\overline{c}}$ players is pairwise stable if $\underline{c} < \overline{c} \leq \frac{1}{6}$.

Notice that the pairwise stability condition does not depend on the number of nodes of each type or on their positions within the heterogeneous cycle.

$\square$

Proof. Lemma 2:

(i) Heterogeneous lines of length three such that two nodes of the same type are not consecutive.

In this structure, every existing link costs $\overline{c}$ to each player. If any link is broken, the central player becomes part of a pair, receiving the gross payoff $1/2$, and the peripheral player becomes isolated, getting the payoff 0. Then,

- central node: $\frac{2}{3}-\overline{c}-\overline{c} \geq \frac{1}{2}-\overline{c} \Leftrightarrow \overline{c} \leq \frac{1}{6}$.
- peripheral node: $\frac{1}{3}-\overline{c} \geq 0 \Leftrightarrow \overline{c} \leq \frac{1}{3}$.

The links are sustained if $\overline{c} \leq 1/6$.

The cost for each peripheral player to form a new link is $\underline{c}$, in which case an odd cycle is created and each player receives the gross payoff $1/2$. Then, as the payoffs are the same for both peripheral nodes,

- create if $\frac{1}{2}-\overline{c}-\underline{c} > \frac{1}{3}-\overline{c} \Leftrightarrow \underline{c} < \frac{1}{6}$.

The link is not created if $\underline{c} \geq 1/6$, but this condition contradicts $\overline{c} \leq 1/6$, and so the structure is not pairwise stable.

(ii) Lines of length four or above.

We first focus on the even lines. In these structures, each node receives the gross payoff $\frac{1}{2}$. Consider the node connected to a peripheral player. It has to sustain two links in the even line, whereas if it kept the connection with the peripheral player only, it would still receive the gross payoff $\frac{1}{2}$ while sustaining just one link, which makes it strictly better off for any positive value of the cost.

We now focus on the odd lines with five or more nodes, m. In these structures, the set M is composed of the odd nodes, so $|M| = (m+1)/2$. Therefore, $|L| = (m-1)/2$ and $r = |L|/|M| =$

$(m-1)/(m+1) < 1$. Accordingly, the gross payoff of the odd nodes is $x_{odd} = r/(1+r) = (m-1)/2m$ and the gross payoff of the even nodes is $x_{even} = 1/(1+r) = (m+1)/2m$.

Consider the link between a peripheral player and the subsequent node. If it breaks, the peripheral node becomes isolated, so getting the payoff 0, and the interior node becomes the extreme of an even line, so receiving the gross payoff $\frac{1}{2}$. Being $c_i^N = \{\overline{c}, \underline{c}\}$ the cost for the node i connected to the peripheral player of sustaining the link that it is not considering breaking, the link with a peripheral player of the same type is sustained if $(m+1)/2m - c_i^N - \underline{c} \geq 1/2 - c_i^N \Leftrightarrow \underline{c} \leq 1/2m$ (and if $\overline{c} \leq 1/2m$ when the peripheral player is of different type).

Consider now the link between two interior nodes. When it breaks, the node occupying the even position in the odd line becomes the extreme node of an even line, receiving the gross payoff $1/2$, whereas the node occupying the odd position in the odd line turns into the extreme node of a new odd line of length $\widetilde{m} < m$, getting the gross payoff $(\widetilde{m}-1)/2\widetilde{m}$. Being $c_i^N = \{\overline{c}, \underline{c}\}$ the cost for any interior node i of sustaining the link that it is not considering breaking, when the two interior nodes are of the same type, the even node keeps the link if $(m+1)/2m - c_i^N - \underline{c} \geq 1/2 - c_i^N \Leftrightarrow \underline{c} \leq 1/2m$, whereas the odd node keeps the link if $(m-1)/2m - c_i^N - \underline{c} \leq (\widetilde{m}-1)/2\widetilde{m} - c_i^N \Leftrightarrow \underline{c} \leq (m-\widetilde{m})/2m\widetilde{m}$. Thus, the link is sustained if $\underline{c} \leq \min\left\{\frac{1}{2m}, \frac{m-\widetilde{m}}{2m\widetilde{m}}\right\}$. Analogously, when the two interior nodes are of different types, the link is sustained if $\overline{c} \leq \min\left\{\frac{1}{2m}, \frac{m-\widetilde{m}}{2m\widetilde{m}}\right\}$.

Take an odd line such that the two peripheral nodes are of the same type. If the line connecting the two peripheral nodes were created, an odd cycle would result, implying that each node receives the gross payoff $1/2$. Thus, the link will not be created if $\underline{c} \geq 1/2m$. If the line is homogeneous, keeping all the links requires $\underline{c} \leq (m-\widetilde{m})/2m\widetilde{m} < 1/2m$ (the last strict inequality coming from the fact that $m \geq 5$), which contradicts $\underline{c} \geq 1/2m$. If the line is heterogeneous, keeping all the links requires $\underline{c} < \overline{c} \leq \min\left\{\frac{1}{2m}, \frac{m-\widetilde{m}}{2m\widetilde{m}}\right\}$, which contradicts $\underline{c} \geq 1/2m$.

Take an odd line such that the two peripheral nodes are of different types. Notice that it is always possible to connect one of the peripheral nodes with an interior odd node of the same type. If such a link were created, the resulting structure would be an odd cycle connected to an even line and each player would get the gross payoff $1/2$. Thus, such a link will not be created if $\underline{c} \geq 1/2m$. As this line is by definition heterogeneous, keeping all links requires $\underline{c} < \overline{c} \leq \min\left\{\frac{1}{2m}, \frac{m-\widetilde{m}}{2m\widetilde{m}}\right\}$, which contradicts $\underline{c} \geq 1/2m$.

(iii) Even cycles.

In these structures, each player receives the gross payoff $1/2$. However, if a link is broken, the resulting structure is an even line and, again, each player gets the gross payoff $1/2$. Therefore, the players that broke the link are strictly better off in the line, as they sustain a single link rather than two for any strictly positive value of the costs.

$\square$

Proof. Theorem 1:
Suppose that there are only two nodes and that they are of the same type. If a link between them were created, each node would receive the gross payoff $1/2$. Then, the link is not created if $\underline{c} \geq 1/2$.

Now suppose that there are three or more nodes. In that case, there will always be at least two nodes of the same type. Then, $\underline{c} \geq 1/2$ is sufficient to prevent the creation of any link: preventing the connection between two nodes of the same type also prevents the connection between two nodes of different types, as the former link is cheaper than the latter. $\square$

Proof. Theorem 2:
Notice the following:

(a) Two pairs never create a link to connect themselves. The reason is that the gross payoff of the nodes creating the link remains $1/2$, so the new structure makes them strictly worse off for any strictly positive value of the costs, as they have to sustain two links rather than one.

(b) To prevent the formation of a link between an isolated node and the extreme of a pair that is of the same type, $1/6 < \underline{c}$ is required (as for the node belonging to the pair is not profitable to become the central node of a line of length three if $1/2 - c_i^N > 2/3 - c_i^N - \underline{c} \Leftrightarrow \underline{c} > 1/6$, where $c_i^N = \{\overline{c}, \underline{c}\}$ is the cost of being connected to the other node of the pair). Analogously, to prevent the formation of a link between an isolated and the extreme node of a pair that is of different type, $1/6 < \overline{c}$ is required.

Consider a network with the characteristic specified in (i). The condition to sustain the homogeneous pairs is $\underline{c} \leq 1/2$, as it was stated in Lemma 1. To prevent the formation of a link between the isolated node and a pair that is of the same type, $1/6 < \underline{c}$ is required. Since $\overline{c} > \underline{c}$, the previous condition also guarantees that a link between the isolated node and a pair that is of different type will not be formed. The intersection of all the conditions is $\frac{1}{6} < \underline{c} \leq \frac{1}{2} \wedge \overline{c} > \underline{c}$, which makes the network pairwise stable.

Consider a network with the characteristics specified in (ii). Again, the condition to sustain the homogeneous pairs is $\underline{c} \leq 1/2$. However, since there are no pairs of the same type as the isolated node, only $1/6 < \overline{c}$ is required to prevent the formation of links. As by assumption $\overline{c} > \underline{c}$, the intersection of all the conditions is $\underline{c} \leq \frac{1}{2} \wedge \overline{c} > \max\left\{\frac{1}{6}, \underline{c}\right\}$, which makes the network pairwise stable.

Consider a network with the characteristics specified in the first part of statement (iii). Again, the condition to sustain the homogeneous pairs is $\underline{c} \leq 1/2$. As in (i), $1/6 < \underline{c}$ is sufficient to prevent the formation of a link between an isolated node and a pair of the same type, and it also automatically prevents the creation of a link between an isolated node and a pair of different type. Finally, to prevent the formation of a link between the two isolated nodes that are of different types, $1/2 \leq \overline{c}$ is required. The intersection of all conditions is $\frac{1}{6} < \underline{c} \leq \frac{1}{2} \leq \overline{c} \wedge \overline{c} > \underline{c}$, which makes the network pairwise stable.
Consider the particular case $\frac{1}{6} < \underline{c} = \frac{1}{2} < \overline{c}$. $\underline{c} = 1/2$ is the intersection between $\underline{c} \leq 1/2$, sufficient to sustain homogeneous pairs, and $\underline{c} \geq 1/2$, sufficient to prevent the link between two isolated nodes of the same type. Plus, as $\overline{c} > \underline{c}$, $\overline{c} > \underline{c} \geq 1/2$ also prevents the link between two isolated nodes of different types (notice that, whenever there are three or more isolated nodes, there are at least two of them of the same type).

Finally, consider a network with characteristics specified in the first part of statement (iv). In this case, the condition to sustain the heterogeneous pair(s) is $\overline{c} \leq 1/2$, which also sustains the homogeneous pairs, if there is any. Notice that, as there is at least one heterogeneous pair, there is always a node of the same type as the isolated that belongs to a pair. The link between these two nodes is prevented if $1/6 < \underline{c}$ (which is also sufficient to prevent the link between the isolated node and a node of different type that belongs to a pair). The intersection of all conditions is $\frac{1}{6} < \underline{c} < \overline{c} \leq \frac{1}{2}$, which makes the network pairwise stable.
Consider the particular case $\frac{1}{6} < \underline{c} < \overline{c} = \frac{1}{2}$. $\overline{c} = 1/2$ is the intersection between $\overline{c} \leq 1/2$, sufficient to sustain heterogeneous pairs, and $\overline{c} \geq 1/2$, sufficient to prevent the link between two isolated nodes of different types, which allows to introduce one more isolated node different from the previous one. Notice that introducing one more isolated node of the same type is not pairwise stable: as $\underline{c} \leq 1/2$, a link between them will be created. $\square$

Proof. Theorem 3:

Recall from the proof of Theorem 2 that two pairs do not create a link among themselves; that $1/6 < \underline{c}$ is sufficient to prevent the formation of a link between an isolated node and the extreme of a pair that is of the same type; and that $1/6 < \overline{c}$ is sufficient to prevent the formation of a link between an isolated node and the extreme of a pair that is of different type.

Also, notice that:

(a) An odd cycle never creates a link with another structure, including an isolated node, because the player in the cycle creating such a link keeps receiving the gross payoff $1/2$ while paying to sustain three links rather than two.

(b) A link between a homogeneous line of length three and an isolated node of different type can be prevented if $1/6 = \underline{c} < \overline{c}$. If the line is either heterogeneous or homogeneous but of the same type as the isolated node, the creation of a link with the isolated player cannot be prevented. The reason is that the link between an isolated node and the extreme of a length-3 line that is of the same type is not created if $\underline{c} > 1/6$. In the former case, the homogeneous line is sustained if $\underline{c} = 1/6$, which contradicts $\underline{c} > 1/6$. In the latter case, the heterogeneous line is sustained if $\overline{c} = 1/6$, which again contradicts $\underline{c} > 1/6$ because $\overline{c} > \underline{c}$ by assumption.

(c) A pair and a length-3 line such that they have extreme nodes of the same type do not create a link if $\underline{c} > 1/15$. Analogously, a pair and a length-3 line such that they do not have extreme nodes of the same type do not create a link if $\overline{c} > 1/15$. Also, notice that the central node of a line of length three does not create a link with a pair for any strictly positive level of the costs, as its gross payoff remains invariant after the creation of such a link.

(d) Two homogeneous length-3 lines of the same type do not create a link if $\underline{c} \geq 1/6$; analogously, two homogeneous length-3 lines of different types do not create a link if $\overline{c} \geq 1/6$. On the contrary, a link between a heterogeneous length-3 line and another length-3 line cannot be prevented. The reason is that a heterogeneous line always has one extreme that can connect with an extreme of the same type of another line (regardless of whether this line is homogeneous or heterogeneous). This link is not created if $\underline{c} \geq 1/6$, but the heterogeneous line is sustained if $\overline{c} = 1/6$, which contradicts the previous condition because $\overline{c} > \underline{c}$ by assumption.

Consider a network with the characteristics specified in (i). Homogeneous odd cycles with at most $1/2\underline{c}$ players are stable if $\underline{c} \leq 1/6$. When adding two isolated nodes, each of a different type, the whole network is pairwise stable by just preventing the link between them, as the cycles do not connect either with an isolated node or among themselves. Then, the network is pairwise stable if $\underline{c} \leq \frac{1}{6} \wedge \overline{c} \geq \frac{1}{2}$. Notice that either pairs or lines of length three cannot fit in this network, as a link with the isolated node of the same type as the extreme node is not created if $\underline{c} > 1/6$, which makes the cycles unstable.

Consider a network with the characteristics specified in the fist part of statement (ii). Homogeneous odd cycles with at most $1/2\underline{c}$ players are stable if $\underline{c} \leq 1/6$. This condition automatically allows to add to the network either one isolated node or homogeneous pair(s): cycles do not create links with any other component, and $\underline{c} \leq 1/6$ is stricter that $\underline{c} \leq 1/2$, which is the sufficient condition to sustain homogeneous pairs. Then, a network with these components is pairwise stable if $\underline{c} \leq \frac{1}{6} \wedge \overline{c} > \underline{c}$. Note that if there was at least one homogeneous pair of the same type as the isolated node, they would connect as $\underline{c} \leq 1/6$. See case (iv) for the pairwise stable conditions when all pairs are homogeneous and different from the isolated node.
Consider the particular case $\underline{c} = \frac{1}{6} < \overline{c}$. If the network is only composed of homogeneous odd cycles and homogeneous pairs, then there can also be homogeneous lines of length three: cycles and pairs keep being stable, lines are sustained and they do not create links either between themselves ($\underline{c} = 1/6 \geq 1/6$) or with pairs ($1/15 < \underline{c} = 1/6 < \overline{c}$). However, if the network is composed of homogeneous odd cycles and one isolated node, homogeneous length-3 lines in general do not fit: as long as there is one line of the same type as the isolated player, a link between them cannot be prevented (as $\underline{c} = 1/6$ contradicts $\underline{c} > 1/6$). See case (iv) for the pairwise stability conditions when all lines are homogeneous and different from the isolated node.

Consider a network with the characteristics specified in the first part of statement (iii). Homogeneous odd cycles with at most $1/2\underline{c}$ players are stable if $\underline{c} \leq 1/6$, and heterogeneous pairs are stable if $\overline{c} \leq 1/2$ (which makes homogeneous pairs also sustainable, as $\overline{c} > \underline{c}$). Then, the network is pairwise stable if $\underline{c} \leq \frac{1}{6} \wedge \underline{c} < \overline{c} \leq \frac{1}{2}$.
Consider the particular case $\frac{1}{6} = \underline{c} < \overline{c} \leq \frac{1}{2}$. In this case, homogeneous lines of length three also fit in this network: cycles and pairs keep being stable, lines are sustained and they do not create links either between themselves ($\underline{c} = 1/6 \geq 1/6$) or with pairs ($1/15 < \underline{c} = 1/6$).

Consider a network with the characteristics specified in the first part of statement (iv). Homogeneous

odd cycles with at most $1/2\underline{c}$ players are stable if $\underline{c} \leq 1/6$, and so are homogeneous pairs as $\underline{c} \leq 1/6$ is stricter than $\underline{c} \leq 1/2$. If $\overline{c} > 1/6$, given that all homogeneous pairs are of the same type, an isolated node of different type fits, since $\overline{c} > 1/6$ prevents any link between these pairs and the isolated player. Then, the network is pairwise stable if $\underline{c} \leq \frac{1}{6} < \overline{c}$. Notice that if there was at least one heterogeneous pair or one homogeneous pair of the same type as the isolated node, the network would not be pairwise stable because the condition to prevent the link between one of these pairs and the isolated player is $\underline{c} > 1/6$, which contradicts the condition to sustain the cycles.
Consider the particular case $\underline{c} = \frac{1}{6} < \overline{c}$. If this is the case, homogeneous length-3 lines such that all are of the same type and different from the isolated node also fit: cycles and pairs keep being stable, lines are sustained, neither lines nor pairs create a link with the isolated player as $\overline{c} > 1/6$, lines do not create links between themselves because $\underline{c} = 1/6 \geq 1/6$, and lines and pairs do not connect because $1/15 < \underline{c} = 1/6$.

Consider a network with the characteristics specified in (v). Heterogeneous odd cycles with at most $1/2\overline{c}$ players are stable if $\overline{c} \leq 1/6$, and so are homogeneous odd cycles with at most $1/2\underline{c}$ players since $\overline{c} > \underline{c}$. This condition automatically allows to add to the network either one isolated node or pair(s), which can be homogeneous and/or heterogeneous: cycles do not create links with any other component and $\overline{c} \leq 1/6$ is stricter than both $\overline{c} \leq 1/2$ and $\underline{c} \leq 1/2$, which are the sufficient conditions to sustain heterogeneous and homogeneous pairs, respectively. Then, a network with these components is pairwise stable if $\underline{c} < \overline{c} \leq \frac{1}{6}$. Notice that, for these parametric conditions, a link between a pair and an isolated node cannot be prevented as $\underline{c} < \overline{c} \leq 1/6$ contradicts both $\overline{c} > 1/6$ and $\underline{c} > 1/6$, so these components cannot co-exist in this network.

Finally, consider a network with the characteristics specified in the first part of statement (vi). Heterogeneous odd cycles with 3 players are stable if $\overline{c} = 1/6$, which also sustains the heterogeneous line of length three. Since $\overline{c} > \underline{c}$ by assumption, homogeneous cycles with at most $1/2\underline{c}$ are also allowed, so the network is pairwise stable if $\underline{c} < \overline{c} = \frac{1}{6}$. Notice that more length-3 lines do not fit: as $\underline{c} < 1/6$, their extremes would always connect.
Consider the particular case $\frac{1}{15} < \underline{c} < \overline{c} = \frac{1}{6}$. Then, pairs homogeneous and/or heterogeneous also fit: $\overline{c} = 1/6$ is stricter than both $\overline{c} \leq 1/2$ and $\underline{c} \leq 1/2$, so allowing for pairs, and $1/15 < \underline{c}$ prevents the creation of links between the heterogeneous line and a pair. However, since $1/15 < \underline{c}$, the number of players of the homogeneous odd cycle(s) can never be larger than seven. □

Notes

[1]The technical model is provided in the appendix for the reader who may be interested to look at it in more detail.

[2]For example, EU members pay fines based on their GDP, how many votes they have on the EU council and their solvency (e.g. in 2014 Italy was fined with €40 million for illegal waste dumping.)

[3]The connection between welfare effects of trade liberalization in the presence of environmental problems was studied in Baumol (1971) and Copeland (1994), while the effects that trade liberalization has on environmental quality is analyzed in Lopez (1994) and Copeland and Taylor (2013). A great survey on the literature on trade and environment is Copeland and Taylor (2004).

[4]The linkage between network economics and the environment is thoroughly described in Currarini et al. (2016). Gallego and Zofío (2018) rely on transport networks to analyze the relationship between trade openness and the spatial location of economic activity.

[5]Topics range from the diffusion of strategic behavior (Jackson and Yariv 2007), technology adoption (Bandiera and Rasul 2006) and innovations (Montanari and Saberi 2010) to microfinance (Banerjee et al. 2013). Good surveys on the topic are Jackson and Yariv (2011) and Lamberson (2016).

[6]This measure gives a greater score to nodes that have a higher (weighted) degree, are connected to other nodes with a high degree or both.

[7]By running simulations with different parameter values, we are able to understand when co-existent equilibria (proposition 1 in the appendix) occurs and when there is complete harmonization (proposition 2 in the appendix). For this threshold, any η value below 1.1 will always be a co-existent equilibrium.

[8]Authors such as Granovetter (1978), Morris (2000), Watts (2002) and Jackson and Yariv (2007) deal also with this approach, although in different contexts than ours.

[9]Our use of simulations is justified by the necessity pointed out in Lamberson (2016) who argues that to understand how the structure of networks influences diffusion, it is necessary to rely on different methods of analyses.

[10]This chapter is based on a published paper with the same name written with Carlos Mendez. Please refer to https://www.mdpi.com/2227-7099/7/2/52

[11]Directed networks can have a node connect to another without the latter necessarily connecting to the first. Weighted networks are those with weights in their links, which allows for asymmetric relationships.

[12]We acknowledge and thank the insightful comments of an anonymous referee who helped improving this section.

[13]See the work of Abreu et al. (2005) and Islam (2003) for some comprehensive reviews of this literature.

[14]Assortativity refers to the tendency of nodes in a network to connect with others with similar characteristics while dissasortativity implies the opposite case.

[15]The simplest form of beta convergence, also known as absolute beta convergence, is commonly used for the study of production units that share common technological and institutional environments.

[16]For the labor productivity convergence analysis, however, 107 industries are considered. This is because there is no systematic data on the number of workers for the Housing industry (JIP code 72).

[17]From a conceptual standpoint, however, using the number of work-hours allows for a more precise definition of labor productivity.

[18]We do not take into account self-loops in the networks since communities are defined considering only linkages between different nodes.

[19]There is an important statistical difference when comparing the regression lines of Figure 11. In panel (a) the relationship is statistically significant, whereas in panel (b) it is not. Indeed, when we estimate a linear relationship for the 1990–2012 period the regression line is actually flat.

[20]Based on panel (a) of Figure 11, relatively low productivity industries are those whose labor productivity was less than 6 in log terms. Although this threshold is arbitrary, its selection is just for illustration purposes.

[21]As we noted in the introduction, community detection algorithms sometimes produce communities with some overlap. In our case this means that there may be some industries from the non-service sector present too. Ways to solve this type of issues are actively being researched in the field.

[22]We tested and compared these results with the Louvain algorithm (Blondel et al., 2008) as a robustness check. The resulting communities obtained mostly coincide with those from the Newman (2006) algorithm we used.

[23]Notice that the algorithm $\mathscr{A}(g)$ assigns isolated players the payoff 0 because they simply cannot bargain.

[24]The homogeneous pair is defined as two nodes of the same type connected.

[25]The heterogeneous pair is defined as two nodes of different types connected.

[26]The homogeneous line of length three is defined as a component of three players of the same type which can be transformed into a 3-player cycle by adding one link.

[27]The heterogeneous line of length three such that two nodes of the same type are consecutive is defined as a component of three players of different types which can be transformed into a 3-player cycle by adding one link between two players of different type.

[28]The homogeneous odd cycle is defined as an odd cycle in which all the nodes are of the same type.

[29]The heterogeneous odd cycle is defined as an odd cycle in which there are nodes of the two types.

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