International Automotive Production Networks: How the web comes together

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Abstract

This paper intends to highlight the structural characteristics of the world automotive trade network and analyze the dynamics of its spatial distribution over time. We use data on trade flows for 172 countries for the years 1996 and 2009 and apply social network analysis tools. The empirical results show that auto network has become denser, more extensive and integrated over time, depicting a centre-periphery structure in which regional clusters play a prominent role. Strong agglomeration forces generated by companies' desire for large and rich market access with minimum transportation costs are balanced by the search for new high-potential markets.

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1. Introduction

This paper intends to contribute to the literature on New Economic Geography (NEG) by providing empirical evidence on the relationships between new trade theory and the spatial distribution of economic activities for the automotive industry.

NEG has a well-defined yet broad objective: it seeks to provide a detailed description of the spatial inequalities that emerge as the outcome of a full-fledged general equilibrium model (Krugman, 1991; Fujita *et al.*, 1999). The numerous works that have developed NEG generally share some assumptions that fit perfectly with the auto industry: (i) space is heterogeneous, generating specialization and trade; (ii) markets are imperfectly competitive and operate under increasing returns to scale; as a result, the location of firms can be explained primarily in terms of the search for privileged access to large, wealthy markets and the desire to relax the competitive pressures imposed by other firms; (iii) transportation is unavoidable and costly when production is not perfectly divisible; and (iv) externalities in production and consumption exist. Therefore, the spatial distribution of economic activities can be viewed as the outcome of different combinations of all these assumptions, in other words, as a complex balance between two types of opposing and mutually reinforcing forces: agglomeration (or centripetal) forces and dispersion (or centrifugal) forces.[1] Among the forces that feed the different NEG models, noteworthy is the home market effect, circular causation (à la Myrdal) in the configuration of a core-periphery structure, location hysteresis, input-out linkages and the bell-shaped curve of spatial development (Baldwin *et al.*, 2003; Fujita and Thisse, 2009).

In spite of NEG's unquestionable contribution to introducing spatial factors into models rigorous enough to be considered in the analytical canon of mainstream

[1] In the simplest 2x2x2 model (Krugman, 1991), two stable spreading equilibria result: agglomeration of one of the sectors in one region when transportation costs are very low, and dispersion of this sector in two regions when transportation costs are very high. In this model, Krugman basically adds the interregional mobility factor (workers and firms choose a location) to his new trade theory model (Krugman, 1980). From this stylized model, different and more complex assumptions have been added. For a discussion of the core model and several of its extensions, see, for example, Ottaviano and Thisse (2004).

economic theory, its own precursors have pointed out that those models are too stylized and simple to adequately represent the real economic geography and thus become relevant from a policy-making standpoint. Therefore, “now it is time to use them to provide the backdrop for less tight, more empirically motivated studies” (Krugman, 2000, p. 59). In this paper, we take up the Krugman's challenge in the analysis of the world automotive industry. One of the main shortcomings of these NGE theoretical models is the dimensionality problem: they only account for two sectors and two regions. However, NEG has been precisely what reminds us that regions are interconnected and that any change that directly involves only two regions now generates spatial spillover effects that are unlikely to leave the remaining regions unaffected. These complex impacts vary in non-trivial ways with the properties of the graph representing the spatial economy. Additionally, NEG has emphasized that spatial frictions between any two regions are likely to be different, which means that the relative position of the region within the whole network of interactions matters (Krugman, 1993; Fujita and Thisse, 2009). In this respect, it is worth noting that the access to several markets is a key issue faced by firms when making their location choices (Thomas, 2002) and thus also influences the way they organize their production, management, and outsourcing, both within and across firms. As NEG also tells us, these two facts mean that the spatial structure of the economy should be considered endogenous from a political and investment standpoint.

At the international level, some of clearest evidence of how these complex interactions between countries and regions influence the way companies organize their production and vice-versa is the emergence of international production networks in most manufacturing sectors. Currently, one of the most fragmented sectors is the automotive industry.

The extent to which these strategies have been implemented in the auto industry is reflected in the spectacular increase in the world automotive trade in general during the past decade (from 1996-2009, it grew at a cumulative annual rate of 5.4 percent in nominal terms) and in the particularly high dynamism of the intermediate commodity flows, with an annual cumulative growth rate of 6.2 percent (almost two percentage points over final goods), increasing its share of total world auto trade from 50 to 56 percent.

The main objective of this paper is to make sense of how these cross-border production blocks are evolving over time on the basis of NEG. In particular, we compare the structural characteristics of the world auto network in 1996 and 2009. As mentioned above, this is a challenging task since their structural development implies highly complex direct and indirect interactions between individuals, firms, nations, and institutions (Arribas *et al*., 2009). In order to overcome NEG's shortcomings when considering this complexity and to reconcile its results with empirical interpretations, in this paper we apply social network analysis tools and graph theory to international trade flows by exploiting recently-developed indicators. Network analysis is an appropriate method for studying such issues because if the nature of international trade is shifting, then the structure of the trade network should display some differences over time. Additionally, applying network analysis to international trade can complement other empirical analyses of trade that put countries' characteristics at the forefront (e.g., the gravity model of international trade) since it places more emphasis on the relationship between units in the graph and on the structure of the system itself than on the units' attributes, which are generally left in the background.

Although these techniques have not been very extensively used in economics to date, the approach is not new in international economics and specifically in trade analysis. Recent examples include Garlaschelli and Loffredo (2005), Kali and Reyes (2007), Kali *et al.* (2007), Arribas *et al.* (2009), Fagiolo *et al.* (2008), and De Benedictis and Tajoli (2011). All of these studies focus on analyzing the world trade network and accurately explore the properties of the system in terms of trade flows, partners, and links. Most of them suggest that there is strong heterogeneity between countries, with nations playing very different roles in the network structure, but there is only a limited effort in these studies to try to explain these findings on the basis of trade or location theories. Additionally, to the best of our knowledge, this approach is a pioneering perspective in the analysis of international production network dynamics in general and of the automotive industry in particular. The structural characteristics of global automotive networks have been analyzed by several meritorious works in recent years (e.g., Humphrey and Memedovic, 2003; Sturgeon *et al.* 2008, 2009; Sturgeon and Van Bieserbroeck, 2010, 2011); in this paper we offer an empirical analysis with a solid analytical framework in order to complement these more descriptive contributions.

The article is organized as follows. In section 2, we briefly explain the main network analysis tools used in this research. Section 3 describes the structural features of the world automotive trade network. Section 4 studies the composition of the centre of this network and its evolution over time. Section 5 analyzes the changes in the role of the central countries within the auto network. Section 6 offers some concluding remarks.

2. Social Network Analysis

2.1. General description

Social Network Analysis is based on mathematical graph theory. When a graph is used as a model of a social network, points (nodes or vertices) represent actors, while the lines connecting the points (edges or arcs[2]) represent the ties between those actors. In the context of the world automotive trade network (WATN, henceforth), the vertices are the trading countries (N=172) and the lines represent the trading flows between any two partners: exports and imports. In particular, we consider the WATN from two complementary standpoints. First, we consider the mere presence or absence of a trading relationship between two countries by setting the generic entry of the (binary) adjacency matrix (A) $a_{ij}^{t} = 1$ if and only if exports from country i to country j reported by the importer (e_{ij}^{t}) are strictly positive in year t, and $a_{ij}^{t}=0$ otherwise.[3] Nevertheless, if we only consider the binary network, we run the risk of valuing links the same way regardless of whether they actually carry very weak or very strong flows; i.e., we might disregard the heterogeneity of link importance (Fagiolo, 2010). In order to consider this heterogeneity, we also analyze the intensity of the interactions, and then consider the network to be weighted. A single graph in the ensemble of weighted networks is completely specified by its generic matrix W whose entry w_{ij} represents the intensity of the link from vertex i to vertex j. For the particular case of WATN analysis, the values of w_{ij} represent the value of exports from country i to country j reported by the importer. Since we are interested in comparing the structure of the WATN at two different moments of time, we also define rescaled weights relative to the total yearly trade flows as follows:

[2] An arc is an ordered pair of nodes, with sourcing and incoming countries, while an edge does not establish any order between the pair of linked nodes.

[3] Self-loops, i.e., links connecting i with itself, are not typically considered. This means that $a_{ii}=0$ for all i.

$$w'_{ij}(t) \equiv \frac{w_{ij}(t)}{w_{tot}(t)}$$

where $w_{tot}(t) \equiv \Sigma_i \Sigma_{j \neq i} w_{ij}(t)$. In this way, trend effects are eliminated and we obtain adimensional weights that are automatically deflated, allowing for consistent comparisons across different years and commodity types (Squartini *et al.*, 2011b). The sequence of *NxN* adjacency and weight matrices (A^t, W^t) for t =1996 and 2009 fully describes the within-sample dynamics of the WATN, and its main characteristics can be summarized by topological measures and paths.

In order to analyze the symmetry of the network and determine whether it is more appropriate to perform a directed analysis (in which lines are arcs) or undirected analysis (in which lines are edges), we calculated the *S* index proposed in Fagiolo (2006). Since the asymmetric patterns of both the P&C and final goods networks have been statistically identified, a directed analysis of the network is necessary for both periods analyzed and for both the binary and the weighted descriptions of the WATN.

2.2. Connectivity and centrality

The number of partners and the interaction intensity of countries, as well as the way these patterns have changed over time, will give us a clear idea about the evolution of the connectivity of countries in the AWN. The widest measure[4] of the connectivity or cohesiveness of a network is its *density*, calculated as the number of arcs divided by the maximum possible number of arcs that can exist in networks with *N* nodes. The density of a diagraph (Δ) goes from 0 if no arcs are present to 1 if all arcs are present, i.e., if the network is complete. Density is inversely related to network size, and this is a problem when interpreting or comparing the density of networks. It is better to examine the number of ties in which the vertex is involved: its *degree*.

The degree of a vertex (k_i) is the number of trading links that a given country has established. In a directed graph, the *indegree* of a country (k^{in}_i) is the number of countries that the country imports from, while its *outdegree* (k^{out}_i) is the number of countries that receive exports from this partner. We could therefore say that a country with a high *outdegree* is a highly connected exporter, whereas a country with a high *indegree* is a well-connected importer. Since prominent or central actors in the network

[4] A more extensive and detailed description of the topological measures included in this section can be found in the seminal book by Wasserman and Faust (1994). The corresponding analytical description of this section is presented in Table A.3 of the Statistical Appendix.

are the most active in the sense that they have the most ties to other actors in the network or graph, an actor's degree is important as a centrality measure. An actor with a large degree should be considered a crucial cog in the network, occupying a central location. In contrast, actors with a low degree are clearly peripheral to the network.

In the weighted network, the *node degree* can be replaced by *node strength* (s_i), defined as the sum of weights associated with the links held by each country. The larger the *node strength* of a country, the higher the intensity of the interactions it mediates. It is clear that two countries can have the same node degree and be associated with very different node strength levels. The *average node strength* (*ANS*) of the network can be considered a measure of the weighted WATN's density.

Additionally, we can also calculate the *degree centralization* of a whole network (C_D), i.e., the extent to which a network has a centre, as the variation in the degrees of vertices divided by the maximum degree variation possible in a network of the same size. The index reaches its maximum value of 1 when one country has trading relationships with all other *N-1* countries and the other countries interact only with this one, central country. This is the situation depicted in a star graph. The index attains its minimum value of 0 when all degrees are equal, yielding a regular graph (Freeman, 1979).

Another view of a country's centrality is based on *closeness* or distance (CL_i). This measure focuses on the idea is that a country is central if it can easily trade with all the others. The simplest measure of closeness is calculated as a function of geodesic distances (Sabidussi, 1966; Beauchamp, 1965).[5] We can then define the *closeness centrality* index of each country in such a way that the larger geodesic distances yield lower closeness centrality.[6] The maximum index equals 1, which arises when the country is adjacent to all other countries. The minimum index is 0, which arises

[5] *Geodesic distance* is the shortest sequence of nodes and lines, starting and ending with nodes, in which each node is incident with the lines following and preceding it in the sequence (walk) and in which all nodes and lines are distinct.

[6] To measure *group centralization*, we take into account the variation in the closeness centrality of vertices divided by the maximum variation in closeness centrality scores possible in a network of the same size. This index also reaches its maximum value (one) when one country "chooses" all other N-1 countries and the other countries have length 2 geodesics to the remaining (N-2) actors. This is the situation illustrated in a star graph (Freeman, 1979). If the directed network is not (strongly) connected, complications in the calculation of this index arise because there are no paths between all the vertices, so it is impossible to compute distances between some vertices. This is the case in the WATN, so we do not use closeness centralization in our analysis. We can instead calculate the variance of the average standardized actor closeness indices, which summarizes the heterogeneity among the individual closeness centralities (Wasserman and Faust, 1994).

whenever one or more countries are not reachable from the country in question. It is worth noting that this type of centrality depends not only on direct ties but also on indirect ties.

An additional approach to centrality is the idea that an actor is more central if it is more important as an intermediary in the network. In this research, we shall apply the *random-walk betweenness centrality* index proposed by Newman (2005) and Fisher and Vega-Redondo (2006) to measure this role .[7] The idea is to measure the effect of a marginal increase in the exports of source country *o* which results in a simultaneous increase in the imports of target country *t*. Such a shock maintains a constant aggregate value for all trading flows in the network. We are interested in how this impulse for trade works its way through each of the *N* countries in the network. An increase in imports in the target country will have important primary, secondary, and tertiary effects on the trading links of all countries in the network, and our aim is to find out how central each of these countries is in the overall pattern of changes in trading activity that follows from this particular impulse. The *random-walk betweenness* of vertex *i* ($RWBC_i$) is equal to the number of times that a random walk starting at *o* and ending at *t* passes through *i* along the way, averaged over all *o* and *t*. In the WATN, we could regard this index as a measure of the extent to which a country is crucial for the integration of the network. Group centralization indices based on *betweenness* (*BCN*) allow us to compare different networks with respect to the heterogeneity of the *betweenness* of their members in such a way that the index reaches its maximum value (unit) in the star graph. Its minimum value (0) occurs when all actors have exactly the same *betweenness* index (line graph).

To extend the *betweenness centrality* index to the directed weighted networks ($RWWBC_i$), we follow the proposal by Fisher and Vega-Redondo (2006) which generalizes the index developed by Newman (2005) in such a way that it captures the effects of the magnitude of the relationships that each node has with its partners, as well as the strength of the node in question. This means that the more central countries are more influential because they have a higher number of direct connections, which are also characterized by high intensity. In their formulation, the probabilities of being

[7] Another possibility is to calculate the *betweenness centrality* of a vertex as the proportion of all geodesics between pairs of other vertices that include this vertex. The index takes values between 0 and 1 (Freeman, 1977; 1979). Unlike the closeness indices, these *betweenness* indices can be computed even if the graph is not connected.

"chosen" assigned to the arcs with greater trading flows are higher than those assigned to weaker arcs.

2.3 Assortativity

Any two countries with the same degree can acquire different importance in the network due to the extent to which their partners are themselves connected to the network, i.e., if they also have a high degree. To measure how much the partners of each country *i* are themselves connected to the networks, we can compute the *average nearest-neighbor degree* (ANND), i.e., the average number of partners of the neighbors (partners) of country *i*. This quantity involves indirect interactions of length two. Countries with the largest degree and ANND are typically the ones with the most intensely interactive relationships. In the binary directed WATN, the ANND can be expressed in five ways: *in-out*, *in-in*, *out-in*, *out-out*, *tot-tot* (Squartini *et al.*, 2011a). The first half of these five expressions indicates the trading relations between the country considered and its partners: *in* indicates that we consider the country to be an importer and *out* that we considered it to be an exporter; the second half indicates the trading relationships of the trading partners of the country analyzed. To illustrate, the ANND *in-out* of country *i* would quantify the average number of export partners of those countries from which country *i* imports. It may well be the case that countries with many links only trade with poorly-connected countries. This is the case with so-called *disassortative networks*. Conversely, it may be the case that better connected countries also tend to trade with other well-connected countries, i.e., an *assortative network* (Fagiolo *et al*., 2008).

In the same way, one might assess how much the partners of a node are themselves characterized by high strength by computing either the *weighted average of nearest-neighbor node degrees* (WANND) or the arithmetic *average of nearest neighbor strengths* (ANNS) (Barrat *et al.*, 2004 and Squartini *et al.*, 2011b). Similar to the binary case, we could analyze five possible directed relations.

2.4. Clustering

Another important feature of network structure concerns the extent to which a given country is clustered, i.e., how much the partners of a country are themselves partners.[8]

[8] Another way of measuring this property is by using the *clustering coefficient* (Watts and Strogatz, 1998, Szabó *et al.*, 2005, Fagiolo, 2007) which is calculated as the ratio between the number of all directed triangles actually formed in the network with *i* as one vertex and the number of all possible triangles that *i* could have formed, no matter what the direction of their arcs.

In particular, to identify clusters of countries that are closely connected because they all share a particular minimum degree within the cluster, we apply the so-called *k-cores* analysis. A *k-core* is a maximal subnetwork in which each vertex has at least degree *k* within the subnetwork, i.e., each node is adjacent to at least a minimum number, *k*, of the other nodes in the subgraph. A *k-core* identifies relatively dense subnetworks, so they help us to find cohesive subgroups. By removing the lowest *k-cor*es from the network until the network breaks into relative dense components, we can find cohesive subgroups as long as a component is a maximally (weakly) connected subnetwork (Seidman, 1983).

3. The International Automotive Production Network

3.1 The Data

To analyze the structural evolution of the automotive trade network, we have used the data from United Nations COMTRADE Database, which offers detailed information on international trade flows for practically every country in the world. In accordance with the Combined Nomenclature (1992) classification, we created separate matrixes of trade between countries for the exchange of automotive final goods and their corresponding parts and components (henceforth, P&C); we did this for 172 countries in 1996 and 2009 (Table A.1 in the Statistical Appendix). The selection of these 172 countries was based in the availability of data for both of the periods analyzed. The use of P&C trade as a suitable proxy for participation in international production networks is commonplace. Because of their intermediate nature, P&C foreign exchanges must necessarily be targeted at assembly or incorporation into a further stage of production in another economy (except spare parts). The final assembly tasks should be also considered in the analysis since in recent years there has been a notable expansion of network activities from pure production and assembly of P&C to final assembly (Athukorala, 2011). From standpoint of the international production networks, studying the final automotive goods export network is particularly relevant, since in doing so we are considering those countries operating in the last stages of the value chain, i.e., in assembly of P&C into the final goods and their subsequent export. The trade data are bilateral export/import as reported by the importing country and measured in nominal

U.S. dollars.[9] We restricted our analysis to those import flows whose value is higher than or equal to 3 percent of the country's total imports of the specific commodity considered.[10] Following the HS1996 categories identified by Türkcan (2009) and the SITC Rev.2 categories recognized by Kaminski and Ng (2001) for auto P&C, we provide a more extensive and complete code list for automotive final goods and their P&C corresponding to HS1992 (Table A.2 in the Statistical Appendix).

3.2. Evolution of the Structural Features of the World Automotive Trade Network

In Table 1, we compare some of the structural characteristics of the automotive network over time, specifically in 1996 and 2009, distinguishing between P&C and final goods. First of all, regarding the evolution of the connectivity of countries in the WATN and focusing on the P&C network, the slight growth over time in their density and degree indicates that countries have, on average, increased the number of partners with which they have trading relations. Nevertheless, only around 4% of all possible links are established *de facto*. Therefore, the P&C network has become denser and more extensive.

[Insert Table 1]

The second result that can be extracted is that a progressively star-structured P&C trade network is emerging, with a small group of highly connected countries in the centre having trade relations with the vast majority of the other countries, and with most countries having a very small number of partners, in particular, having trade relations only with those central countries. The rising standard deviation and the higher centralization index would suggest this uneven increasing integration within the network.[11] In Figure 1 we clearly can see this pattern of heterogeneity. In this sense, it is also interesting to note that, according to the closeness centrality index, over time, more countries are easily reachable within the network and distances between trading

[9] Since for many developing and underdeveloped countries the import data reported by the importer country were somewhat incomplete, we have filled in the missing data using the corresponding trade flows reported by the exporters to these economies.
[10] The choice of the trade data to be used is not neutral in describing the network. Although import data are generally considered more reliable in terms of coverage and completeness (Athukorala, 2011), we must be aware that the use of import data can give rise to a network structure that is different than the one found with exports (as shown by Kali and Reyes, 2007 and De Benedectics and Tajoli, 2011).
[11] We should issue a warning here. In a network with multiple lines, such as the world automotive trade network, the degree of a vertex is not equal to the number of its neighbors. Therefore, the star-network does not necessarily have maximum variation, and we may obtain centralization scores over 1.00. For this reason, we have symmetrized the networks before calculating the network centralization index, considering then the number of neighbors instead of the number of lines.

economies seem to be shortened insofar as more direct trading relations have emerged within the network. Therefore, we can say that the trade integration of the P&C auto network has increased over time. We can also see in Figure 1 that not only there are few countries with a higher number of links, but there are even fewer that are intensely connected. In fact, the distribution of countries' strengths is even more asymmetric and peaked than the distribution of the degrees, although it seems that this heterogeneity is being softened over time. As a result, one can say that auto P&C network has a centre-periphery structure in terms of connectivity and intensity.

[Insert Figure 1]

Nevertheless, it should be noted that when distinguishing between the export and import sides, the P&C export network exhibits a clear and increasingly star-shaped structure, whereas the P&C import network has no clear centre and instead looks rather like a regular graph. Figures 2a and 2b clearly show this difference. There is a small nucleus of countries exporting P&C to the rest of the world and a large proportion of countries which do neither produce nor export P&C but, of course, need to buy them either for assembly into final goods or, as is the case with the vast majority of countries, as spare parts.

[Insert Figures 2a, 2b]

The third interesting result is the high correlation between countries' connectivity and their trading strength (Figure 1), and the equally high correlation between their degree and their closeness (Figure 3). This would mean that, on average, highly connected and integrated countries are also the most intensely connected. As expected, this high correlation is attributed exclusively to the export side, i.e., the more connected exporters are also the most intense exporters. It is also interesting to observe how the variability in strength is fairly high for those countries with a relatively low degree, while from a certain degree onwards, countries are able to maintain intense trade relationships.[12]

[Insert Figure 3]

[12] We can also appreciate a relatively high and stable average disparity in countries' strengths measured by the Herfindahl index (0.3). Most countries in the network have fairly diversified trading links, although there is also a small group of economies that have trade flows with very few countries. This high diversification is even more evident for exports than for imports.

We also detect in Figure 3 that those few countries with increasingly intense relationships are also the countries that play a more prominent role as intermediaries within the network insofar the RWBC indices for the binary version of WATN are almost perfectly correlated with node degrees (0.98 in 1996 and 2009), and for the weighted version the indices are also very highly correlated with both degrees and strengths, although this trend is on the decline (0.93 and 0.86, respectively, in 1996; and 0.91 and 0.81, respectively, in 2009). Moreover, these *betweenness* indexes have, on average, increased over time, especially the weighted indexes, which indicates that the countries that play an important gatekeeper role within the network are intensifying their function. Additionally, we can observe for the whole network that the binary *betweenness centralization* index is increasing over time, as is, to a much higher extent, the weighted *betweenness centralization* index, which indicates the increasing importance of hubs in the WATN. This dynamic is the consequence of the development of the central sector-specific knowledge and innovative activity in these intermediary countries. Most of the sector's economic activity must pass through their territory because the majority of the critical technical and engineering tasks are developed within or near them (Sturgeon *et al.*, 2008). This centralization strategy is not incompatible with the increasing product differentiation that requires access to certain new markets and encourages companies to adapt their models to new consumer preferences. These modifications seldom affect the core structure of the automotive products.

The fifth interesting finding is that those central, highly connected countries are increasingly extending those relations towards poorly-connected countries. In other words, the automotive network is gradually expanding around the world, including new countries that traditionally used to not actively take part in the network. We can observe this tendency in Table 1 insofar as ANND is much higher than the average degree and has increased slightly over time. In Figure 4 we can also observe that the correlation between both variables in 1996 was -0.5, which indicates a moderately disassortative network. However, by 2009 it had increased to -0.6 so the disassortative nature of the network has become rather more pronounced.

[Insert Figure 4]

Considering the directional relations in the network, we can observe that there is no relation between the number of countries to which every economy exports P&C and the number of foreign customers or providers that these economies themselves have.

Additionally, while at the beginning of the period analyzed, the fact that a country purchased P&C from many other countries (indegree) did not imply that these countries themselves imported from many other economies (ANDD *in-in*), in 2009 a negative but weak relation could be observed between both patterns: the suppliers of countries with many other suppliers tended to have few import partners themselves. Conversely, the positive but weak correlation between *indegrees* and ANND *in-out* observed in 2009 indicates that exporters that sell to countries with many other suppliers increasingly tend to also export to a high number of economies. The combination of both tendencies confirms the existence of an increasingly close network in which a small group of countries produces and exports P&C to supply the majority of countries.

When the weighted network is considered, we can observe in Figure 5 that the disassortative nature of the network is far from being evident insofar as the correlation between NS and ANSS is negative but fairly weak in magnitude. This means that, on average, the partners of countries with intense relationships do not necessarily have intense trading links themselves. In other words, not all countries in the network have strengthened their links to the same degree; only one group of countries has intensified their flows. Therefore, we are witnessing an incipient strategy in which by expanding their production networks to new, low-trade countries, companies are trying to take advantage of scale economies and low labor costs, especially for the most standardized and low added-value P&C, while the bulk of P&C is still produced and sold by a small number of central countries. Additionally, we can observe that both the ND and the WANND have increased during the period, although there is no correlation between them. This indicates that well-connected countries' partners do not necessarily have intense trading links with all their partners.

[Insert Figure 5]

The sixth important point in our analysis worth remarking on is that the aforementioned structure for P&C network is basically repeated for the final goods export network in that no statically significant differences were found between both networks for the majority of the structural indicators: only a small group of countries is highly-connected and intense exporters of final goods, and the exporters of final goods have a highly diverse portfolio of partners (Figure 6). In fact, when we analyzed the interaction between the P&C network and the final goods export network, we observed that the most intense P&C importers and exporters were also the most intense exporters of final goods. And, as expected, we found that the heaviest P&C exporters were also the most highly connected countries in the export markets of final goods. However, it seems that the heaviest exporters of final goods do not necessarily have a high number of foreign providers of P&C, even though they intensely buy P&C from them. This parallelism signals an important structural change in the auto network from the nineties to today. Traditionally, the P&C sector has been less concentrated (less centralized) than the final assembly sector (Wells and Rawlinson, 1994; Sadler, 1997), but over time, the intense concentration and internationalization process experienced by the component sector in order to be able to source to assembly firms on a world-wide basis has brought the centralization indices of both networks closer. We can observe how the P&C network has become even more centralized than the final goods network by 2009 (Table 1). Nevertheless, P&C firms are still more geographically scattered in their production and sales patterns than auto final goods companies. This change is the consequence of two main facts. First, the intermediate transportation costs in the automotive industry lead to automakers to locate close to the end markets. This decision is further encouraged by the pressure exerted by some countries for local content.[13] Secondly, it reflects the relational form of the linkages between suppliers and assemblers caused by the high complexity and modularity of the auto P&C. In this sense, carmakers' preference for developing local supplier bases through a mixture of encouraging follow-sourcing by major transnational companies in P&C, where large suppliers follow their customers' investment abroad, and the upgrading of existing local suppliers (Humphrey and Memodovic, 2003), foster the synchronized structural evolution of the final and P&C networks.

[Insert Figure 6]

Finally, an essential result of this study is that the *k-core* indicators[14] show that on average countries tend to establish trade relationships with partners that also trade P&C with each other: For the whole P&C network in 2009, 42 (34 in 1996) countries had trading links with at least another 10 (9 in 1996) countries in the same group. However, the highest P&C export *k-core* in both periods includes a very small number

[13] For example, in China, local content regulations require at least 40% of local content for sedans and 50% for complete vehicles. In addition, joint ventures are also pressured into accepting parts produced by their partners' subsidiaries (Nag *et al*., 2007).

[14] The *k-core* analysis for the whole network is conducted by taking into account the number of neighbors. The results would be different if we considered the number of lines. The number of lines will be considered in the input k-core and output k-core analysis.

of countries: 8 in 1996 and 12 in 2009 (with k=4 in both years). In both cases, those groups formed a strong component, so they were very cohesive. Regarding the core of the final goods export network, this is much more stable than the P&C network as it is made up of the same 7 countries in both periods (with k=4 in 1996 and k=5 in 2009). These findings would suggest that regional, local and/or traditional ties play a very important and increasing role in the shaping of the network, especially for final auto goods.

We further investigated this issue and calculated the density of auto networks for the different continents; we observed a positive continental effect for Asia and America, although the most striking case is Europe.[15] The European automotive final goods and especially P&C networks, though far from being complete, have a higher density than the other continental networks, in both 1996 and 2009. And they are far higher than the density of automotive world trade networks: 0.15 versus 0.04. That means that, on average, the probability of two European countries having trading links with each other is almost four times higher than the probability of two countries in the world having trading links. We should also note the evolution shown by the structure of Asian automotive networks over time: The density and average degree have increased markedly in the auto P&C sector (from 0.06 to 0.09).[16] These strong regional patterns at the operational level have been noted in previous works like Lung *et al.* (2004), Dicken (2005, 2007), Sturgeon *et al.* (2008) and Sturgeon and Van Biesebroeck (2011). Once again, we see that regional P&C production tends to feed final assembly plants which produce largely for regional markets.

In accordance with the aforementioned results, we can say that from a structural point of view, the WATN both for P&C and final goods has become, on average, denser, more extensive and more integrated, although not all the countries in the network have strengthened their links to the same degree; it is a star-shaped network, with this centre-periphery structure increasing especially in terms of connection for P&C network, and with a rising importance of hubs and regional blocks. After this

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[15] These results are very much in line with those found in Gil-Pareja *et al.* (2009) who, using a gravity model, find a positive trading *continental bias* for Asia, Oceania, America, and Europe. For the particular case of the automotive industry, several studies have indicated its strong regional structure (Dhiel, 2001; Sturgeon *et al.*, 2009; Baldwin, 2009).

[16] Regional integration in Asia remained limited for the promotion of some countries of their own national industries (Malaysia and Indonesia) and for the significant differences among the countries regarding their preferences for vehicle types (Humphrey and Memedovic, 2003). These limitations have been softening in recent years.

analysis, several questions are raised: Which countries form the center of this star-shaped auto network? In which direction has the auto network extended? How has the role of these countries changed over time (if it has)? Which forces have made this core-periphery structure emerge? Can this evolution be explained on the basis of new trade theories? We will analyze these questions in the next sections.

4. Main Actors within the World Automotive Trade Network

Table 2 shows the most- and best-connected countries in the automotive P&C network for 1996 and 2009. It also displays the *outdegrees* and *outstrengths* of those countries in the final goods network. In 1996, the central nucleus of the export P&C network was made up of Japan, Germany, and the USA. Those three were the most connected countries and the most intense exporters. Other Western European countries such as the United Kingdom, Italy, and France were also widely and strongly connected. On the other hand, Canada and Mexico, which both had a significant presence in the P&C export markets, were nevertheless very narrowly linked. The principal change in 2009 was that China had emerged overwhelmingly in the centre, together with the aforementioned countries. Not only had it increased its links spectacularly over the period but those links were strong enough to overtake Germany in *outstrength*. It is also worth mentioning the escalating behavior of Korea. This country was already highly connected in 1996 but its intensity was weak, but by 2009 its numerous trade links had translated into high export intensity. Some Eastern European countries, such as Hungary, Poland, and the Czech Republic have also gained importance in the P&C export network, creating numerous and intense trading links.

[Insert Table 2]

As we have seen in Section 3.2., there is a strong correlation between centrality indices. In particular, Germany, Japan, the United States, Italy, France, the United Kingdom, Korea, Spain, Belgium-Luxembourg, and the Netherlands were the most central, reachable, and go-between countries in the network in both 1996 and 2009. China deserves separate mention, for it has risen to the top positions in all centrality indexes from its already high place in 1996. Additionally, it is noteworthy that these central countries not only sell their P&C to those non-producer countries but that there is also an intensive flow of P&C from them toward other (less powerful) P&C producers in the centre of the network. In fact, in 1996, the densest *k-core* (and strong component) was composed of a European cluster (Belgium-Luxembourg, France, Germany, Italy, Spain, and United Kingdom) plus Japan and the USA. In 2009, Asian countries like China and Korea and some Eastern European countries like the Czech Republic, Hungary, and Poland were part of the densest and most cohesive group of exporters. Therefore, new groups of countries have joined the old clusters and the latter have created new links with them, expanding the scale and scope of the network, as already pointed out by the increasing dissasortativeness of the network in terms of connectivity. It is also remarkable how in 1996 countries such as Mexico, Poland, and Hungary were not among the most important intermediary economies in the network, while in 2009 they were among the top. Therefore, we can observe a displacement/expansion within the regions of some of the crucial sector activities that some years ago were exclusively concentrated in the lead companies' home countries.

As expected from the structural analysis, in the final goods export network we find the same main players as in P&C networks, although with several important nuances. The heaviest and more intense exporters in both years were Japan and Germany. The United States, Canada, France, and the United Kingdom are also highly connected, but their links are weaker than those of the two central economies. Other countries such as Italy, Belgium-Luxembourg, and especially Spain have a lower level of connection, but they were also very active exporters of final automotive goods in both periods.[17] In 2009, some Asian countries such as China and Thailand joined this group of widely connected countries. Although their *outstrengths* in the final market are still much lower than those of traditional exporters, their increasing levels of trading links indicate major potential for expansion of their weight in the near future. Similar to the case for P&C, Korea is translating its previous high level of connection into elevated *outstrength*, while and Mexico and Canada, which are scarcely connected, have very significant *outstrengths* in the final automotive market thanks to their exceptionally strong links. Of course, for these two countries, the proximity to large markets, in particular the United States means a very high concentration of their exports, most of which are regional sales. Finally, some emerging economies are increasing their presence both in the P&C and the final goods markets. This is the case with the Czech Republic, Poland, and Brazil. However, countries with a scant presence in P&C

[17] Belgium-Luxembourg, France, Germany, Italy, Japan, Spain, and the United Kingdom were the countries which made up the highest *k-core* for final goods.

markets, such as Turkey and Argentina, are also gaining ground as final exporters. As we will see in next section, this is a common pathway in the expansion of the auto network: new countries first host assembly activities and then increase their production of auto P&C.

5. Changes in the Role of Countries within the World Automotive Trade Network

In section 3.2 we found that, for the whole sample in general, the most intense P&C importers are also the most intense P&C exporters and that both are usually the most intense exporters of final goods. However, the detailed analysis by country in Table 2 shows clear disparities between central countries regarding their role within the WATN. It also shows how the alterations in the composition of the centre have affected the countries differently. Table 2 reveals that the most outstanding fact is that a significant portion of advanced countries have lost *outstrength* in the networks, both in P&C and final goods networks. The USA and Japan have been especially affected by these losses. However, we can observe that the main losses have affected the *outstrength* figures, while the decreases in both *instrengths* and final goods *outstrengths* have been almost insignificant. These data suggest a movement of P&C production from these countries to other less-developed regions, in particular to China, other Asian countries, and Eastern Europe, while a significant portion of the final assembly stages in the value chain remains at home.

In order to further investigate to which extent this evolution reflects companies' search for the exploitation of spatial heterogeneity among regions in terms of more efficient production through specialization and trade (as classical international trade theories would posit) we will calculate the traditional *Balassa* indices applied to P&C exports and imports and also to auto final goods. Table 3 displays the specialization coefficients for automotive P&C exports and imports and also for final goods exports. For P&C exports, values higher than one indicate specialization in the production and export of these P&C.[18] In the case of imports, values higher than one mean a specialization in P&C assembly, since imported P&C will necessarily be incorporated

[18] The Specialization Index is calculated as $SI_i = [(\sum_j w^{P\&C}{}_{ij}/([(\sum_j w^{m}{}_{ij})]/[(\sum_i\sum_{i\neq j} w^{P\&C}{}_{ij}/)/(\sum_i\sum_{i\neq j} w^{m})]$ where $w^{P\&C}{}_{ij}$ are the exports of automotive P&C of country *i* to country *j* ; $w^{m}{}_{ij}$ are exports of manufacturing goods from country *i* to country *j*. We have relaxed the 3% restriction in the calculation of SI, considering the total trade flows.

into other higher added-value P&C or into final goods. When the import specialization is indeed part of a vertical specialization strategy, which means that the destination of the final goods is export, then the country also benefits from a comparative advantage in the export of final goods. According to this argument, we can classify countries into three main categories or groups. The first group (G1 in Table 3) is made up of pure producers and exporters of P&C. These countries will display a coefficient higher than one for specialization in P&C exports. The second group (G2) contains those countries which are specialized in labor-intensive assembly tasks. For these countries, the specialization coefficient for P&C import will be higher than one. The third group includes those countries that are major exporters and very active importers of P&C. These countries are dually specialized and are the ones that participate most actively in the networks (Kaminsky and Ng, 2001). This behavior could result from two circumstances. The first possibility is that the country is a heavy P&C exporter but is also highly dependent on foreign intermediate imports: it imports P&C that are transformed into other more downstream P&C, which are then exported (G3). The second possibility is to export upstream P&C, which are transformed into more complex P&C abroad and are re-imported from the country for assembly into the final product, which is then exported (G4). Bearing in mind its shortcomings, the analysis of the trade balance can be an indicator of which of the two situations prevails.

[Insert Table 3]

We can observe that, despite its important losses in P&C export *outstrengths*, Japan remains being a pure producer of P&C which are destined for both export and domestic assembly. The final automotive goods produced at home are of course very much consumed domestically, but they also heavily targeted at export, as reflected in the high specialization index for auto final goods. Nevertheless, in recent years, Japanese companies have been further expanding their already-high local capacity in North America and Europe and have relocated their plants to serve China, other South-East Asian countries, and other developing countries locally (Shimokawa, 2010). It should come as no surprise that a country as developed as Japan belongs to this group. Its industry has followed a clear vertical specialization strategy at the highest technological stages. Over the period analyzed, Korea and China have hosted important auto multinationals which have made them pure producers and exporters of P&C. Korea is consolidating its position in the global network as an assembler and exporter of final goods as well, whereas given China's huge domestic market, for the time being most of the P&C it produces and imports are assembled inside the country and targeted at satisfying its own demand.[19] Nevertheless, the high number of trading links that the country is creating leads us to expect the export market to be a future goal of the assemblers settled in China. Figures for *instrength* in Table 2 and import specialization indexes indicate that, these three countries import and re-import relatively very low amounts of components, attaching importance to the domestic component industry, which has been traditionally very protective (Nag *et al.*, 2007).

Countries such as the United Kingdom and the United States seem to follow a very different strategy: they are specialized in the assembly of P&C, which they mostly import or re-import (the latter is very much the case with the United States), mainly into final goods that they either consume domestically or export. While the United Kingdom is more export-oriented and therefore follows a clearer vertical specialization strategy, the large US domestic market absorbs a relatively higher proportion of the national final automotive production, although we should bear in mind that the United States is the third largest world exporter of automotive final goods. It is also interesting to observe how in the mid-nineties the United States was dual specialized, while today it has lost its comparative advantage as a producer and exporter of P&C and is increasingly focused on the assembly of final goods to be sent abroad. We can also observe how Belgium-Luxemburg has lost a large part of the comparative advantage in assembly that it held in the mid-nineties as well as also its position as an export platform; it seems that this downsizing process will continue in the coming years.

The other prominent countries in the network show a dual specialization. And, with the exception of Hungary, all of them are also specialized in final exports. It therefore seems that these countries have advantages in all stages of the value chain, and the companies located in these countries follow vertical specialization strategies. As a matter of fact, they are the most active actors in the international shared production systems. However, there are some differences between them. Countries such as Germany, France, and Mexico import P&C, which are either transformed into other more downstream P&C destined for foreign markets or are assembled into the final product in their territories and then exported. In this sense, Germany's role is remarkable. Not only does it import P&C to be transformed into higher added-value

[19] China's import share for final goods is less than 3%.

goods, but it is also the main exporter of final goods, so it plays a prominent role as an assembler. Together with these three traditional countries in the industry, several Eastern European countries are coming to the fore in the automotive network by transforming imported P&C into other downstream P&C, which are either exported directly for assembly abroad or are assembled domestically into final goods and then exported from their territories. This is clearly the strategy of the Czech Republic. Other countries, such as Hungary, mainly transform imported P&C into higher added-value P&C, which are re-exported back for assembly.[20]

Finally, economies such as Spain and Canada, though also dually specialized, show higher advantages in assembly. They export P&C that are transformed into higher added-value P&C abroad and then re-imported for assembly into the final goods, which are then consumed domestically or exported. They can be considered export platforms of final automotive goods. As in the case of the USA, the United Kingdom, and Germany, Spain and Canada are very powerful assemblers despite not being economies with low-cost labor or having, *a priori*, apparent labor cost advantages in the world economy. However, emerging countries such as Brazil, Argentina, Thailand, and Turkey, which have relatively cheaper labor costs but also certain technological and productive capacities as well as a minimum development of infrastructures and institutions, are increasing their involvement in the automotive network as assemblers. On the other hand, countries such as Sweden are clearly losing a large proportion of their traditional advantages in labor-intensive tasks to these emerging countries.

After this analysis, we can observe that, as Krugman (1980) points out for the industrial sector, the distribution of economy activity in the automotive industry arises from a balance of agglomeration and dispersion forces. The agglomeration forces are generated by companies' desire for large market access in terms of population and purchasing power coupled with a minimization of transportation costs. This comparative advantage of some economies, based more on market size than on production costs, is what it is expected for industries like automotive that operate in segmented markets under imperfect competition and with increasing returns to scale and intermediate transportation costs. In fact, the exploitation of the advantages of the international division of labor requires extensive markets, with the market size

[20] Audi and Opel (GM) built engine assembly plants in Hungary to assemble parts imported from Germany and re-export them back to assembly operations in Western Europe (Humphrey and Memedovic, 2003).

determining the optimum degree of production fragmentation (Jones *et al.*, 2005). We can observe that only large (huge in some cases) emerging markets with an intermediate level of development or economies very close to and/or integrated into large markets are being included within the more extensive and integrated auto network. This circumstance has maintained the traditional imbalances in the spatial distribution of the automotive industry, implying an important and dual degree of specialization among the largest and most developed economies. When the economies are large enough to absorb their production, the domestic market is the main consumer; however, when the economies attract a more than proportional share of firms, they also become export platforms.

Yet together with these agglomeration forces, the search for new and remote markets with high potential in terms of demand that would allow companies to avoid market saturation in traditional markets is acting as a powerful dispersion force. In this process, in contrast to many other industries, in the majority of emerging countries the agglomeration of the final sector in a particular new country (or region) does not occur because there was a previous concentration of the P&C industry in the same country or region; instead, final assembly is often the first step, while the development of a P&C sector comes later (Sturgeon and Van Biesebroeck, 2011). The relational linkages and the follow-sourcing strategy in the automotive industry then fosters a circular process à la Myrdal (more than in other industries) in which market size and the intermediate transportation costs are the key factors. Those countries that are geographically close to large existing markets or that are large or rich enough to support vehicle assembly are becoming intermediaries in the production of certain P&C that can be exported to the rest of the world. At the same time, these new peripheral economies offer both growing domestic markets for automotive final product and low-cost production sites as workers, with strong incentives from the installation of new manufacturing companies, become more skilled and earn higher salaries, which is again a market expansion force, at least while the gap in costs between the core and periphery remains sufficiently large (Toulemonde, 2006). In spite of this process of relocation towards new large and/or low-cost peripheral countries and the loss of production and trade flows among some core and traditional peripheral countries, one could not say that we are witnessing a deindustrialization process in the sector à la Kuznets. Transportation costs and location hysteresis, the weight of history, are playing a prominent role in keeping companies tied to the same country (or region) for long periods of time. The existence of longstanding regional clusters that try to obtain the maximum agglomeration rents is clear evidence of this fact.

5.3. Automotive Parts and Components Subnetworks. A Factorial Intensity Approach

In general, in capital- and technology-intensive industries like the automotive, the production of P&C is considered to be relatively capital-intensive while their assembly is relatively more labor-intensive (Kim, 2002; Athukorala, 2009). However, there are considerable differences between automotive P&C in terms of factorial intensity, which in turn will influence transportation costs, transaction costs, and the extent to which scale economies can be exploited. These factors are very much taken into account by auto companies in their outsourcing and location decisions. It is interesting, then, to explore whether the structural transformations and changes in countries' specialization that the previous analysis has revealed depends on the factorial intensity of auto P&C. In order to do this, and following Peneder (1999), we will differentiate four P&C subnetworks according to their factorial intensity: mainstream-driven, capital intensive-driven, technology-driven and labor-intensive-driven[21].

We can observe in Table 4 that in 1996 the most connected and intense exporters and the most intense importers of P&C were the same for all four types of P&C. In all factorial P&C subnetworks, Japan, Germany, and the USA were among the three most connected exporters in 1996 (Table 4). Only in the labor-intensive subnetwork, Italy was in third position after Japan and Germany. In 2009, China became the third highest exporter in capital-intensive behind Germany and Japan and the irrefutable leader in the other three factorial subnetworks. The other two top positions were occupied by Germany and Japan, with the exception of the labor-intensive network, in which Korea and the USA are the second and third largest exporters, respectively.

[Insert Table 4]

In the mainstream subnetwork, China's entry into the market, and to a lesser extent other emerging countries such as the Czech Republic, Poland, Korea, and Thailand, has seriously affected most of the main countries in the sector, especially the

[21] Peneder (1999) identified five groups rather than four. The fifth group refers to marketing-driven P&C. Since, in the case of the automotive industry, this category includes only two items which account for only 0.3% of the total trade in automotive P&C we have decided not to analyze this category separately. The mainstream-driven category refers to those items in which input combinations do not share a major reliance on any particular input factor.

USA and Japan, but also the United Kingdom, France, Italy, and Canada. In this context, Spain's resistance to the fierce and direct competition from the new exporters is highly meritorious. In Table 5 we can observe that the dynamics in this network have become China as the major P&C market for Japanese companies: Japan sends these components to China for assembly and domestic consumption. Additionally, the USA has substituted half of its P&C supplies coming from Japan and Canada with Chinese P&C, although it has also maintained a significant import share from its traditional partners. And in Europe, Germany has extended its network toward several Eastern European countries, especially the Czech Republic; but also, albeit to a lesser extent, to China.[22] Its traditional EU-15 trading partners, together with Japan and the USA, have been the main countries affected by this change. It seems that the Japanese strategy of transferring part of its production to China has led German companies to buy some of their components from there.

[Insert Table 5]

There is clear German supremacy in the capital-intensive network, which has increased over time.[23] The transformation in this subnetwork has been softer than in other networks. The entry of China in the network has been more timid in terms of intensity, but its presence hovers over the other producers as a dire threat since it has opened a very broad market, with 110 export partners. The most striking change in this network is the sharp drop in the USA's *outstrength*. Japan has substituted its imports from the United States and a portion of those from Germany and other developed countries with P&C sourced mainly from China, though also from Korea, Thailand, Indonesia, and even the Philippines. Conversely, some Japanese exports of these P&C are now going to Asian countries, although the United States remains the principal market for Japanese capital-intensive P&C. Additionally, together with Europe, China receives an important proportion of German capital-intensive P&C, mainly to be assembled and consumed domestically. The United Kingdom has been especially affected by this change in Germany's strategy. Finally, in this network the United States shows a marked saving cost strategy, shifting a large portion of its supplies from Japan, Canada, and several European partners to Mexico and China, mainly, as well as Korea and India.

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22 An interesting explanation about automotive companies' strategies in Europe can be found in Freyssenet and Lugn (2007).

23 Here we are referring to P&C such as engines' parts, bumpers, breaks, and gear boxes.

In the labor intensive P&C network, we can observe a clear redistribution of the market over time with an extraordinary increase in the presence of China as an exporter of this type of P&C.[24] All high labor-cost countries (with the exception of Austria) have lost their share in favor of emerging and relatively lower labor-cost economies. The USA and the United Kingdom have again been severely affected by this process. This transfer of production is also reflected in the decreasing correlation between the countries that import the most intensely and those that export the most intensively. Over time, the new EU members, as well as China and other remote countries such as South Africa, have gained importance as suppliers to Germany of labor-intensive P&C, mainly in detriment to the United Kingdom, Italy, and Spain. On the export side, Germany continues to provide labor-intensive P&C to the main assembler countries around the world; it sells not only to the senior EU members but also to China, the United States, and Russia. Japan has shifted the vast majority of its foreign labor P&C purchases from the United States and some from Europe to China and Mexico. In parallel, Thailand, Indonesia and especially Malaysia have also lost part of their weight in Japanese imports to the benefit of China. As a result, after the USA, China has become the second largest destination for Japanese exports, and the USA has changed its main source of foreign supplied labor-intensive P&C from Canada and Japan to China and Mexico.

But the most volatile factorial subnetwork throughout the period analyzed has been the technology-driven P&C subnetwork.[25] In this market, we can observe a massive shift of Japanese imports from suppliers in the USA to other Asian suppliers, mainly China (62%) but also Korea and other countries. Japan's strategy is echoed in the United States, in part caused by it: the substitution of Japanese, Mexican, and Canadian imports with Chinese and Korean technology-driven P&C.[26] In parallel, two main changes have been observed in Europe. The first is a transfer of production from Germany to Hungary using the latter country as an export platform for this kind of P&C to China, among other countries. Secondly, Sweden and France have largely reduced their markets, and their destinations have shifted to new markets such as China, Korea,

[24] Here we are referring to P&C like electrical equipments or seats.
[25] Here we are referring to P&C like chassis, cassettes players or engines.
[26] A detailed explanation of this shift in US imports is given in Klier and Rubestein (2008, 2010). Sturgeon *et al.* (2009) focus on the consequences of this dynamic for the Canadian auto industry, and Sturgeon and Van Biesebroeck (2011) analyze the role of Mexico in this evolution.

Turkey (Sweden), and Tunisia (France). After these operations, the importance of this type of production for the European automotive industry greatly decreased.

All in all, we can observe that the prominent countries in all the factorial networks in 1996 have maintained their importance within these networks,[27] although significant new players have entered that have redistributed the market for all types of P&C. This indicates that when firms set up their operations in new places and the transportation costs are sufficiently high, they rarely abandon their home bases completely; they remain rooted there to serve the home market and to supplement offshore production through exports. However, the inclusion of emerging countries in the networks has significantly affected the main countries in the sector. Two common dynamics in the networks, regardless of factorial intensity, have been observed. The first is an intense transfer of activity from the United States and Japan to new economies, mainly Asian countries. As long as the North American and Asian networks are closely linked, the movement of their respective central countries has resulted in both networks experiencing parallel transformations. While this strategy is very typical of American automakers, which tend to systematically break relational ties after the necessary collaborative engineering work with their suppliers has been accomplished and very frequently open re-bid processes in an effort to lower input costs, it signals a profound change in the strategy of Japanese automotive companies, which have traditionally been highly reluctant to move their production abroad and for whom predatory supplier switching used to be almost unheard of (Sturgeon *et al.*, 2008). In fact, this process of outsourcing has taken place in Japan later and less aggressively than in North American companies and even European carmakers. The second dynamic is a German-led extension of the European networks mainly towards the new EU members but also to China. Some of these new countries, some of them huge new markets, have rapidly migrated from simple labor-intensive P&C to more sophisticated technology-driven P&C. As a consequence, global sourcing has caused the list of top suppliers to become more regionally balanced. However, we have observed how the majority of the developed countries, Germany in particular, have kept the production of capital-intensive products at home, which are relatively more complex and tend to have higher transaction costs.

[27] Other recent studies support these findings, showing that those countries with higher levels of connectivity and product diversification remain within the international production networks longer and their trading flows are more stable (Córcoles *et al.*, 2012).

We have also have observed that in 1996 the most connected and intense exporters and the most intense importers of P&C were the same for the four types of P&C and also for final goods. However, we note that in 2009 the correlation between the intensity of trading relations in the technology-driven network and the other factorial subnetworks and final goods was much weaker. This confirms that the need for full co-location of parts with final assembly varies by type of component (Sturgeon and Van Biesebroeck, 2011), depending heavily on the possibilities of exploiting scale economies and transportation costs of any P&C.

Finally, it is noteworthy that in some of these transformations in the WATN the role of industrial policy seems to have been very prominent. For example, in China, national political institutions have promoted innovative policies and trade liberalization programs which have led private Chinese players to step in with modern technology, while direct foreign investment has started pouring in, mainly through the hands of Japanese and US automobile companies. Additionally, China has promoted the consolidation of its traditionally fragmented industry through mergers and acquisitions that have developed the local automotive sector by strengthening the national players (Nag *et al*., 2007). It is also clearly the role of industrial policy to maintain the auto clusters in developed countries, with the sector receiving permanent support from authorities. Finally, the positive impact of the EU in the regional dimension of the European auto network and the contribution of its enlargement to bringing some of the new member states into the WATN is evident (Blázquez *et al.*, 2011, Türkan and Ates, 2011). Therefore, institutions are a key element in the endogenous nature of nations' comparative advantage.

6. Concluding Remarks

In this empirical paper, we have examined the evolution of the world automotive trade network based on the New Economic Geography. For this purpose, the tools of social network analysis and graph theory have been applied to international trade flows of 172 countries for the years 1996 and 2009.

The paper aims to contribute to the literature on NEG in two ways, first by performing empirically-motivated studies which allow their results to be reconciled with those of more theoretical, stylized models, and secondly by offering a novel and robust analysis of the evolution of one of the most internationally fragmented industries in which spatial economies play a central role.

The empirical results show that, from a structural point of view, the world automotive network has become denser, more extensive, and more integrated over time. It depicts a start-shaped structure, with the P&C network increasing this centre-periphery structure in terms of connectivity. We have also observed a clear regional, more than global, conformation of the network, in which hubs are becoming increasingly important. In this sense, new clusters and intermediary countries have emerged, establishing links with old ones, which prevail over time.

These dynamics have meant a significant and increasing diversification of trade over time. Although the Triad (Japan, Germany, and the US) maintain their prominent role in the auto industry, we are witnessing the displacement of some of the existing and/or new production from them to less developed countries such as Eastern Europe, Korea, and above all China, which is emerging as a powerhouse in the network. This has meant significant changes in the role played by central countries within the network. Regardless of the factorial intensity of the networks, we have detected an intense transfer of activity from Japan and especially the United States toward Asian countries and from Germany to the new EU member states, although we have observed a more aggressive quest to exploit comparative advantages in the more labor-intensive and technology-driven P&C. On the other hand, the repositioning of capital-intensive P&C has been much more moderate, and with the exception of the United States those capital-abundant countries have maintained most of their capital-intensive activities at home. In any case, the intermediate transportation costs and location hysteresis keep the companies tied to the same country (or region) for long periods of time.

In general, we have observed two balance forces in the configuration of the network which allow for multiple stable equilibriums. On the one hand, strong agglomeration forces are generated by companies' desire to have access to traditional large, rich markets at minimum transportation costs. On the other hand, the search for new and high-potential markets that would allow companies to avoid market saturation is acting as a powerful dispersion force. In general, companies are trying to minimize the spatial differentiation for those activities which are common to the whole range of products that they sell and that are concentrated in clustered locations near the companies' headquarters and traditional large markets. At the same time, they are trying to differentiate their products to better fit their consumers' preferences and minimize transportation costs, so they are choosing to locate some parts of the process close to the final markets. It is also noteworthy that the role of trade, foreign investment, and industrial policies has been crucial in the balance of these opposing forces.

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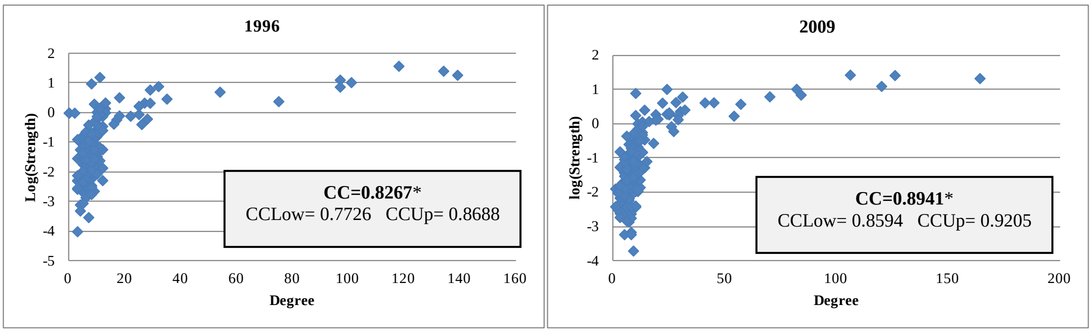
Figure 1. Correlation between *Degree* and *Strength* for P&C WATN (1996 and 2009)



Source: authors' calculation, based on UN COMTRADE. CCLow and CCUp are the correlation coefficients at 5% and 95% confidence intervals

Figure 2a. Automotive P&C. Out-degree Network (2009)

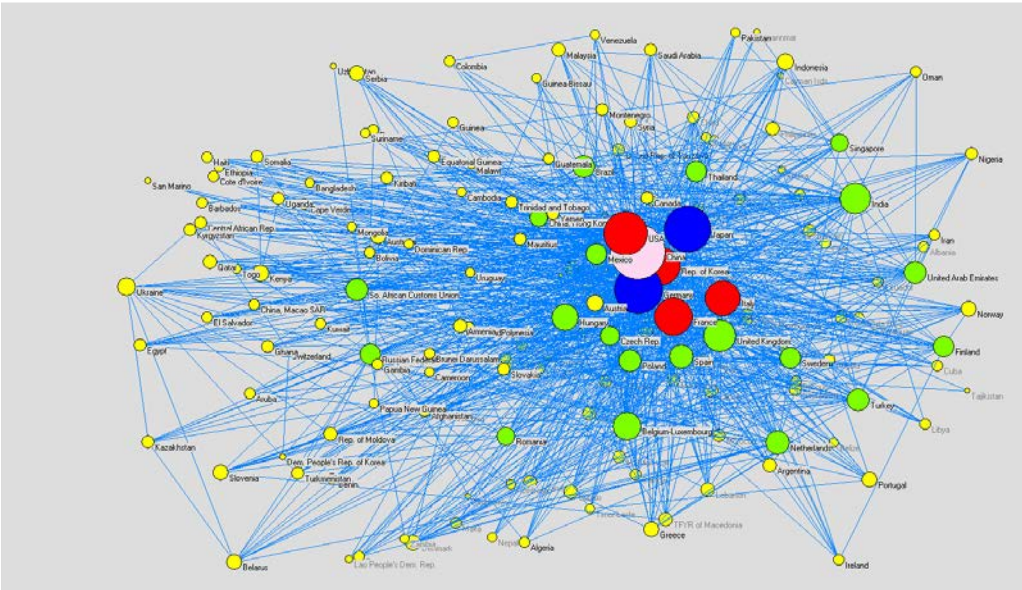
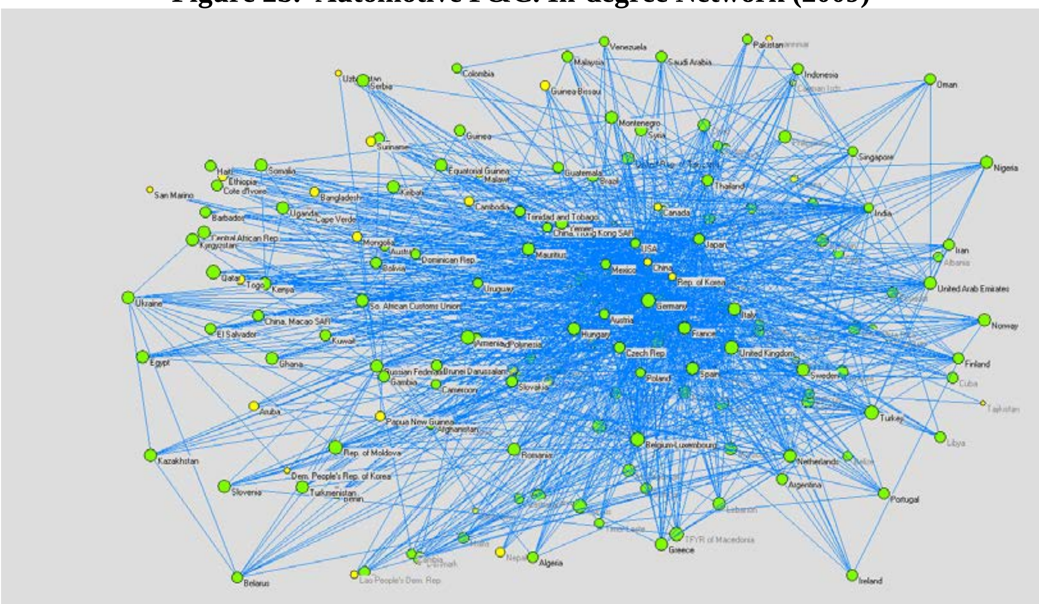
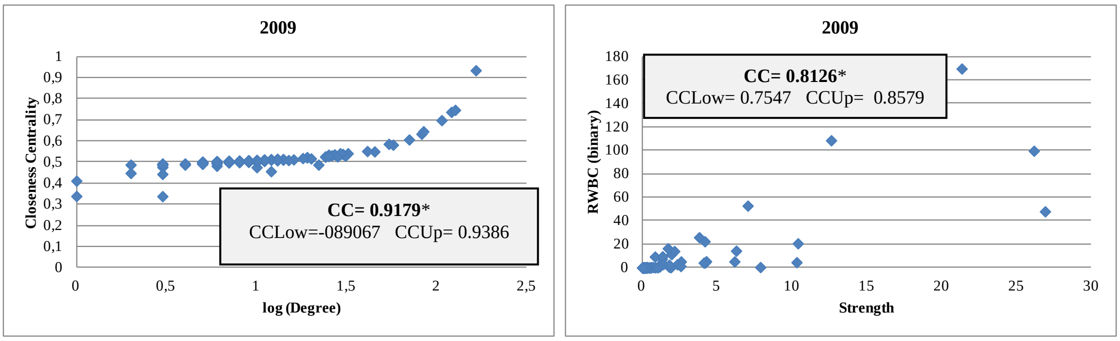


Figure 2b. Automotive P&C. In-degree Network (2009)



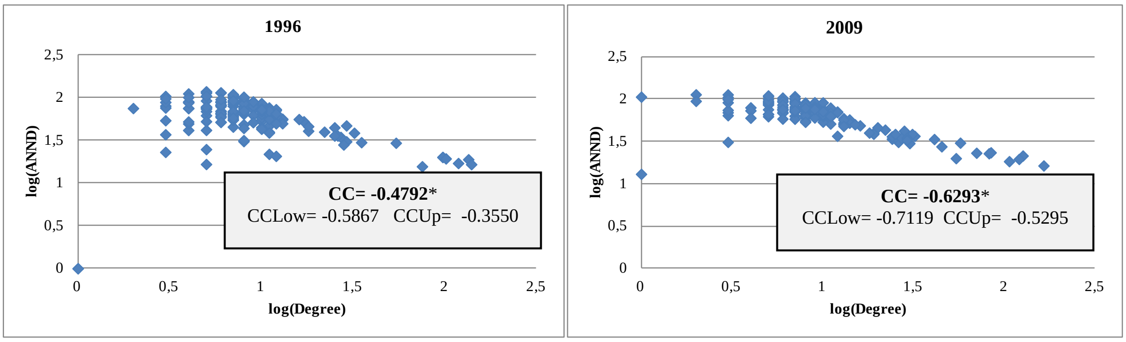
Source: authors' calculation, based on UN COMTRADE using PAJEK. The size of vertices is related to their indegrees/outdegrees

Figure 3. Correlations *Degree* vs *Closeness Centrality* and *Strength* vs *Random Walk Betweenness Centrality* (RWBC) for P&C AWN, 2009



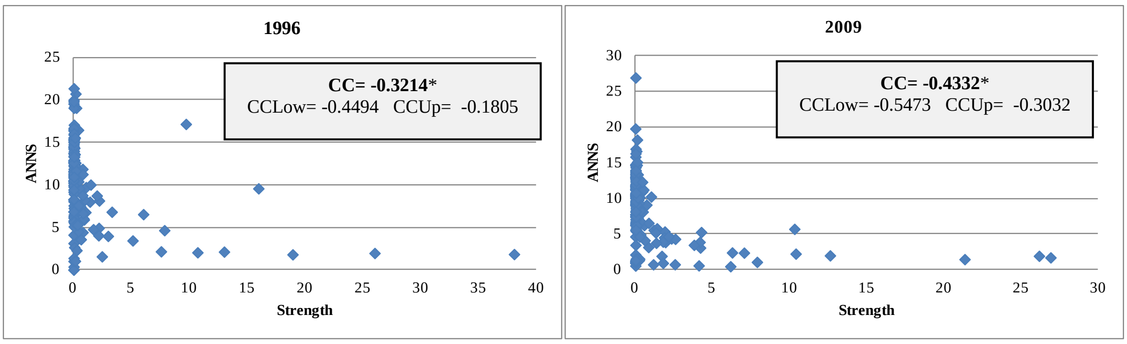
Source: authors' calculation, based on UN COMTRADE. CCLow and CCUp are the correlation coefficients at 5% and 95% confidence intervals.

Figure 4. Correlation between *ANND* and *Degree* for P&C AWN (1996 and 2009)



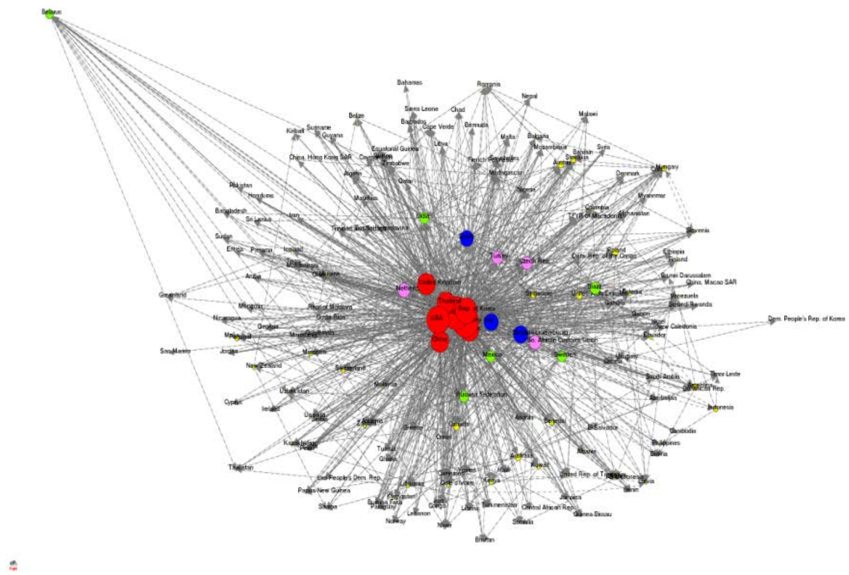
Source: authors' calculation, based on UN COMTRADE. CCLow and CCUp are the correlation coefficients at 5% and 95% confidence intervals.

Figure 5. Correlation between *ANNS* and *Strength* for P&C AWN (1996 and 2009)



Source: authors' calculation, based on UN COMTRADE. CCLow and CCUp are the correlation coefficients at 5% and 95% confidence intervals.

Figure 6. Automotive Final Goods. Outdegree Network (2009)(*)



Source: authors' calculation, based on UN COMTRADE using PAJEK. The size of vertices is related to their all degrees.

Table 1. Topological Measures of the International Automotive Trade Network[a]

Binary Network Indexes	P&C 1996	P&C 2009	Final Goods 1996	Final Goods 2009	Weighted Network Indexes	P&C 1996	P&C 2009	Final Goods 1996	Final Goods 2009
Arcs (#)	1133	1262	1029	1125					
Density	0.038	0.042	0.035	0.037					
Average Node Degree (Number of lines)	13.128	14.616	11.837	12.965	**Average Node Strength**	1.156	1.146	1.153	1.161
In- Degree/Outdegree (Average)	6.564	7.308	5.918	6.482	**Instrength/Outstrength (Average)**	0.578	0.582	0.576	0.580
Average Nearest-Neigbourg Degree (ANND)	66.94	68.16	73.398	67.399	**Average Nearest-Neighbor Strength (ANNS)**	10.239	8.362	11.3777	9.272
Network Centralization	0.691	0.861	0.838	0.781					
In-Degree Centralization	0.032	0.028	0.030	0.038					
Out-Degree Centralization	0.722	0.894	0.866	0.811					
Input Closeness Centrality	0.087	0.084	0.060	0.072					
Output Closeness Centrality	0.093	0.092	0.062	0.078					
Closeness Centrality	0.487	0.509	0.503	0.510					
Random Walk Betweenness Centrality (RWBC)	0.037	0.042	0.039	0.055	**Random Walk Betweenness Centrality (RWBC)**	0.572	3.932	2.774	3.357
Random Walk Betweenness Centralization	0.459	0.529	0.573	0.726	**Random Walk Betweenness Centralization**	19.845	166.683	184.516	181.009

Source: authors' calculation, based on UN COMTRADE

[a] In the Indegree indicators for 1996 and 2009 and the ANND for 1996 there are statistically significant differences (5% significance) between the measures for P&C and Final Goods while for the rest of indicators (Outdegree, Degree, Instrength, Outstrength, Total Strength, ANND for 2009, ANNS, CC, WCC, RWBC) no statistically significant differences are found between the averages for P&C and Final Goods.

Table 2. The Role of Countries in the International Automotive Production Network

	1996						2009					
	Automotive Parts and Components				Automotive Final Goods		Automotive Parts and Components				Automotive Final Goods	
	Outdegree	Outstrength	Indegree	Instrength	Outdegree	Outstrength	Outdegree	Outstrength	Indegree	Instrength	Outdegree	Outstrength
China	23	0.95	6	1.20	6	0.02	160	16.99	4	4.35	63	0.75
Germany	123	17.86	11	8.16	127	22.11	114	16.53	12	9.63	125	25.44
Japan	130	16.75	9	2.18	152	18.43	113	10.07	7	2.55	143	17.59
USA	114	20.27	4	17.79	95	7.99	100	9.49	6	17.42	99	7.87
Korea	71	0.91	4	1.54	86	1.42	80	5.76	4	1.28	90	4.47
France	89	8.06	8	4.95	85	7.71	72	5.60	10	4.79	63	6.11
Italy	90	4.73	7	2.83	56	3.32	61	3.73	9	2.54	38	2.50
India	19	0.07	7	0.35	16	0.04	48	0.49	6	1.22	16	0.15
UK	94	4.39	7	6.32	77	5.54	45	2.35	12	1.45	61	3.97
B&L	21	1.81	8	4.21	36	5.28	34	1.24	11	2.97	39	3.68
Hungary	4	0.54	8	0.23	1	0.02	32	2.80	9	1.38	4	0.09
Netherlands	27	0.53	8	2.45	32	1.10	23	0.93	9	1.65	27	0.39
Poland	4	0.02	7	0.84	0	0.00	22	2.61	6	1.66	6	0.79
Spain	26	3.01	6	4.83	38	5.84	22	2.35	9	3.81	34	6.05
Brazil	18	0.62	9	1.56	11	0.39	21	1.02	9	1.31	19	0.91
UAE	5	0.01	11	0.41	6	0.02	20	0.09	9	1.26	8	0.07
Finland	18	0.42	7	0.48	4	0.05	19	0.30	7	0.54	1	0.00
Mexico	5	5.35	3	4.36	20	4.67	18	5.86	6	4.45	16	5.27
Thailand	7	0.26	2	1.75	3	0.00	18	0.91	7	1.23	60	1.58
SACU	0	0.00	8	0.02	0	0.00	18	0.07	9	0.55	26	0.26
Turkey	11	0.03	7	0.78	8	0.05	17	0.18	12	1.61	22	1.49
Sweden	43	2.90	11	2.21	25	0.76	15	0.79	9	1.15	15	0.39
Russia	19	0.25	9	0.38	20	0.13	15	0.29	10	1.58	16	0.15
Czech Rep.	7	0.50	6	0.53	12	0.14	14	2.39	8	1.72	21	1.68
Singapore	15	0.33	10	1.37	4	0.04	13	0.20	6	1.11	5	0.01
Romania	0	0.00	4	0.13	2	0.01	11	0.71	9	0.69	1	0.03
Indonesia	6	0.02	5	0.94	0	0.00	9	0.28	7	0.91	4	0.05
Austria	13	1.60	5	1.70	4	0.33	8	1.28	6	1.28	6	0.47
Canada	8	5.37	3	10.60	8	12.28	6	2.76	4	5.13	6	5.44
Portugal	5	0.38	6	1.09	6	0.50	6	0.23	7	0.63	3	0.04
Argentina	4	0.28	6	0.78	2	0.36	4	0.19	7	0.83	6	0.88
Slovakia	3	0.09	7	0.12	1	0.01	3	0.80	7	0.99	5	0.46

Source: authors' calculation, based on UN COMTRADE.

Table 3. Specialization of main countries in the automotive sector

		1996			2009		
		P&C		Final Goods	P&C		Final Goods
		Import	Export	Export	Import	Export	Export
G1	Japan	0.44	1.40	1.65	0.70	1.37	2.47
	Korea	0.59	0.52	0.87	0.59	1.38	1.17
	China	0.42	0.48	0.02	0.52	1.02	0.07
G2	UK	1.06	0.82	1.04	1.10	0.86	1.35
	USA	1.12	1.35	0.60	1.19	0.94	0.82
	B&L	1.33	0.55	1.73	0.88	0.47	1.06
G3	Hungary	0.76	3.15	0.58	2.00	3.48	0.80
	Mexico	2.01	2.40	2.20	1.72	2.42	2.27
	Czech Rep.	1.03	1.25	0.83	1.71	2.08	1.70
	Poland	1.20	0.63	0.70	1.43	1.78	1.10
	Germany	1.03	1.31	1.72	1.33	1.20	1.96
	France	0.89	1.27	1.20	1.04	1.16	1.26
G4	Brazil	1.42	1.89	0.67	1.14	1.83	1.39
	Spain	1.99	1.45	2.65	1.68	1.21	2.71
	Canada	2.56	1.42	3.29	1.57	1.20	2.39
	Sweden	1.51	1.88	1.18	1.27	1.16	1.02
	Argentina	1.46	1.53	1.77	1.97	1.07	3.58
	Thailand	1.18	0.55	0.05	1.01	1.04	1.22
	Turkey	0.94	0.74	0.34	1.33	1.02	1.87

Table 4. Parts and Components Automotive Subnetworks

	1996				2009			
	Mainstream Driven Parts and Components Network							
	Outdegree	Outstrength	Indegree	Instrength	Outdegree	Outstrength	Indegree	Instrength
China	32	1.94	6	1.07	152	13.68	5	5.19
Germany	116	19.34	10	8.60	114	17.89	14	9.89
Japan	128	18.03	8	2.78	109	12.33	6	2.71
USA	103	19.12	8	15.30	100	12.87	7	13.37
Italy	89	7.37	7	4.01	78	5.72	10	3.33
Korea	87	2.20	4	1.96	72	3.39	5	1.85
France	94	8.07	8	6.02	69	5.54	10	5.27
UK	94	5.87	8	5.12	49	3.12	9	3.73
Belg.& Lux.	30	2.18	8	3.18	38	2.61	11	3.31
Thailand	23	0.92	5	1.43	32	1.80	8	1.11
Netherland	35	1.80	9	2.99	29	1.32	10	2.25
Poland	6	0.03	9	0.77	24	1.89	6	1.58
Spain	29	2.53	5	3.00	22	2.59	9	2.49
Czech Rep.	10	0.54	6	0.77	17	2.64	8	1.64
Mexico	7	2.42	3	3.52	11	3.09	6	3.41
Canada	4	3.86	2	6.95	7	2.48	4	4.59
	Capital Intensive Parts and Components Network							
Germany	120	20.52	9	6.95	119	24.30	11	9.60
Japan	125	17.57	7	1.25	113	13.32	9	1.80
China	7	0.12	4	1.12	110	4.79	4	6.01
USA	101	21.90	5	17.61	91	10.69	6	13.88
France	75	10.07	7	4.80	78	8.49	8	4.98
Italy	80	4.53	7	2.27	67	4.54	8	2.66
UK	89	4.00	7	9.64	54	1.77	8	4.25
Korea	23	0.51	3	1.35	45	3.33	6	1.53
Spain	19	3.48	5	5.54	37	3.44	6	5.69
Belg.& Lux.	29	1.92	8	4.99	34	1.74	9	3.43
Poland	5	0.03	6	0.56	17	2.93	7	2.20
Sweden	23	1.90	7	2.27	17	0.84	9	1.67
Czech Rep.	8	0.38	6	0.45	13	3.07	7	2.11
Mexico	1	2.39	4	5.38	11	5.00	5	5.32
Canada	6	6.44	2	12.93	3	3.17	4	6.62
	Labour Intensive Parts and Components Network							
China	17	1.85	5	0.62	140	14.59	5	3.27
Germany	114	18.47	11	10.49	108	16.19	11	13.93
Japan	118	11.28	8	2.84	96	9.05	9	2.90
Italy	99	7.91	7	2.77	86	6.35	9	2.64
USA	90	15.21	5	20.05	85	7.69	5	19.29
France	73	6.75	7	5.74	67	5.37	9	5.52
UK	75	4.25	8	5.66	41	0.39	10	4.80
Poland	7	0.62	7	2.40	25	4.71	7	1.94
Belg.& Lux.	21	3.24	8	4.81	22	1.73	10	3.37
Czech Rep.	13	1.71	6	0.69	21	4.45	7	1.70
Austria	13	1.42	8	2.33	19	2.20	7	1.28
Mexico	9	7.46	3	3.31	18	9.00	6	3.68
Spain	20	2.57	5	3.71	17	2.24	7	2.66
Hungary	4	0.85	5	0.36	13	1.61	8	1.24
Canada	9	6.82	3	9.54	9	2.85	4	4.83
Slovakia	1	0.07	6	0.13	8	2.97	10	0.94
	Technology Driven Parts and Components Network							
China	17	3.137	6	1.926	156	34.326	6	2.142
Korea	17	0.639	5	1.715	87	12.491	4	0.887
USA	122	18.082	5	23.299	71	5.088	4	22.4107
Germany	97	11.027	10	8.344	59	4.149	8	8.007
Hungary	7	1.880	6	0.318	57	7.512	8	1.444
India	11	0.046	8	0.068	49	1.476	4	1.963
Finland	43	2.425	7	0.452	47	2.213	5	0.923
Japan	109	15.146	6	3.027	45	2.187	6	3.256
France	72	5.123	11	3.437	41	1.573	9	3.913
UK	77	4.422	9	2.392	35	3.208	10	4.097
Sweden	57	7.167	10	1.176	25	1.227	8	0.572
Mexico	8	12.430	1	3.590	24	8.151	6	4.006
Spain	15	2.639	6	5.501	11	0.608	11	3.132
Austria	8	2.699	6	1.181	7	2.041	9	0.942
Poland	0	0.000	8	0.911	7	1.728	8	1.570
Canada	18	3.985	3	9.025	4	2.240	5	3.648

Table 5. Main Destination and Origins of Automotive P&C. Central Countries in Automotive Network[a]

Automotive Total P&C																							
Germany								Japan								USA							
Exports				Import				Export				Import				Export				Import			
1996		2009		1996		2009		1996		2009		1996		2009		1996		2009		1996		2009	
UK	13,0%	FR	8,6%	FR	12,9%	CZ	10,2%	US	37,1%	CHN	20,6%	US	35,2%	CHN	43,7%	CA	46,3%	CA	35,9%	JP	28,2%	MX	24,8%
FR	10,1%	ES	7,1%	AT	12,3%	AT	8,8%	TH	9,6%	US	20,4%	DE	9,1%	KO	9,3%	MX	18,5%	MX	25,4%	CA	24,0%	CHN	22,9%
B&L	8,5%	UK	6,8%	IT	9,7%	HU	8,5%	UK	4,6%	TH	7,0%	CHN	8,4%	TH	8,1%	JP	4,6%	CHN	3,3%	MX	21,8%	CA	12,4%
ES	8,2%	US	6,7%	UK	9,6%	FR	8,0%	ID	4,2%	DE	4,0%	SE	6,6%	US	7,1%	KO	2,9%	DE	3,2%	DE	5,9%	JP	10,7%
US	7,2%	CHN	6,5%	ES	7,4%	PO	7,8%	DE	3,9%	KO	3,7%	TH	5,9%	DE	6,4%	DE	2,3%	UK	2,6%	BR	2,3%	KO	10,3%
IT	6,4%	AT	5,8%	JP	6,3%	IT	7,2%	HK	3,7%	CA	3,4%	PH	5,7%	PH	4,5%	UK	2,2%	JP	2,1%	FR	2,2%	DE	5,6%
AT	5,8%	B&L	5,3%	US	4,5%	UK	5,6%	CA	3,5%	UK	2,8%	MY	3,6%	ID	4,4%	AU	2,0%	AU	2,0%	CHN	2,2%	BR	1,3%
SE	5,0%	IT	5,2%	HU	4,4%	CHN	4,8%	KO	3,4%	MX	2,6%	KO	3,5%	MY	2,1%	BR	1,6%	VE	1,8%	UK	2,1%	UK	1,2%
NL	4,1%	CZ	4,9%	CZ	3,6%	ES	4,6%	SG	2,8%	ID	2,5%	FI	3,2%	FR	1,8%	AT	1,4%	BR	1,6%	KO	1,6%	FR	1,1%
CH	2,2%	PO	4,7%	PT	3,5%	SK	3,9%	AU	2,6%	BR	2,5%	UK	2,9%	UK	1,8%	HK	1,2%	FR	1,6%	IT	1,5%	IT	1,1%
PT	1,9%	HU	3,9%	B&L	3,4%	JP	3,3%	CHN	2,4%	FR	2,4%	IT	2,3%	MX	1,5%	B&L	1,2%	KO	1,3%	SE	0,8%	TH	1,0%
MX	1,9%	MX	3,4%	NL	2,7%	RO	3,1%	B&L	1,6%	AE	2,0%	ID	2,1%	NL	1,2%	FR	1,2%	SG	1,1%	TH	0,7%	MY	0,7%

Source: authors' calculation, based on UN COMTRADE

[a]Argentina (AR); Australia (AU); Austria (AT); Belgium-Luxembourg (B&L); Brazil (BR); Canada (CA); China (CHN); Colombia (CO); Czech Rep.(CZ); Denmark (DK); El Salvador (SV); Finland (FI); France (FR); Germany (DE); Honduras HN); Hong Kong (HK); Hungary (HU); Indonesia (ID); Israel (IL); Italy (IT); Japan (JP); Malaysia (MY); Mexico (MX); Netherlands (NL); Panama (PA); Philippines (PH); Poland (PL); Portugal (PT); Korea (KO); Romania (RO); Russian F. (RU); Saudi Arabia (SA); Singapore (SG); Slovakia (SK); Slovenia (SI); Spain (ES); Sweden (SE); Switzerland (CH); Thailand (TH); Tunisia (TN); U.A. Emirates (AE); United Kingdom (UK); USA (US) and Venezuela (VE).

STATISTICAL APPENDIX

Table A1. Countries included in the analysis

Afghanistan	Croatia	Italy	Philippines	Uruguay
Albania	Cuba	Jamaica	Poland	USA
Algeria	Cyprus	Japan	Portugal	Uzbekistan
Angola	Czech Rep.	Kazakhstan	Qatar	Venezuela
Argentina	Dem. People's Rep. of Korea	Kenya	Rep. of Korea	Yemen
Armenia	Denmark	Kuwait	Rep. of Moldova	Zambia
Aruba	Djibouti	Kyrgyzstan	Romania	Zimbabwe
Australia	Dominican Rep.	Lao People's Dem. Rep.	Russian Federation	SACU
Austria	Ecuador	Latvia	Rwanda	
Azerbaijan	Egypt	Lebanon	Samoa	
Bahamas	El Salvador	Liberia	San Marino	
Bahrain	Equatorial Guinea	Libya	Saudi Arabia	
Bangladesh	Eritrea	Lithuania	Senegal	
Barbados	Estonia	Madagascar	Serbia	
Belarus	Ethiopia	Malawi	Serbia-Montenegro	
Belgium-Luxembourg	Finland	Malaysia	Seychelles	
Belize	France	Mali	Sierra Leone	
Benin	Kiribati	Malta	Singapore	
Bermuda	French Polynesia	Mauritania	Slovakia	
Bhutan	FS Micronesia	Mauritius	Slovenia	
Bolivia	Gabon	Mexico	Somalia	
Bosnia Herzegovina	Gambia	Mongolia	Spain	
Brazil	Georgia	Montenegro	Sri Lanka	
Brunei Darussalam	Germany	Morocco	Sudan	
Bulgaria	Ghana	Mozambique	Suriname	
Burkina Faso	Greece	Myannmar	Sweden	
Burundi	Greenland	Nepal	Switzerland	
Cambodia	Guatemala	Netherlands	Syria	
Cameroon	Guinea	New Caledonia	Tajikistan	
Canada	Guinea-Bissau	New Zealand	Macedonia	
Cape Verde	Guyana	Nicaragua	Thailand	
Cayman Isds	Haiti	Niger	Timor-Leste	
Central African Rep.	Honduras	Nigeria	Togo	
Chad	Hungary	Norway	Trinidad- Tobago	
Chile	Iceland	Oman	Tunisia	
China	India	Pakistan	Turkey	
China, Hong Kong SAR	Indonesia	Panama	Turkmenistan	
China, Macao SAR	Iran	Papua New Guinea	Uganda	
Colombia	Iraq	Papua New Guinea	United Arab Emirates	
Congo	Ireland	Paraguay	United Kingdom	
Costa Rica	Israel	Peru	United Rep. of Tanzania	

**SACU: Southern African Custom Union: South Africa, Botswana, Namibia, Swaziland, Lesotho*

Table A2. Automotive Commodities included in the Analysis

Final Goods	Auto Parts and Components			
	Mainstream	*Technology Driven*	*Labour Intensive*	*Capital Intensive*
870310	700711	870600	870710	870810
870321	700721	851993	870790	870821
870322	700910	852520	940120	870829
870323	830210	852721	940190	870831
870324	830230	852729	940390	870839
870331	870990	853641	871690	870840
870332	400950	854430	851110	870850
870333	681310	902910	851120	870860
870390	681390	902920	851130	870870
870421	731816	902990	851140	870880
870422	732010	840734	851150	870893
870423	732020	840820	851180	870894
870431	842139	840731	851190	870899
870432	848210	840732	851220	840991
870490	848220	840733	851230	840999
870510	848240	381900	851240	870891
870520	848250	382000	851290	870892
870530	841520		853180	
870540	841583			
870590	841590			
870210	850132			
870290	850710			
870120	850730			
870130	850790			
870110	853910			
870190	853921			
842710	401693			
870410	841330			
	841391			
	841430			
	841459			
	842123			
	842131			
	848310			
	840890			
	401110			
	401120			
	401210			
	401220			
	401310			
	401699			
	842549			
	842691			
	843110			

A3. Definition of Topological Measures

Binary Network			Weighted Network		
Index	**Definition**	**Parameters**	**Index**	**Definition**	**Parameters**
Density	$\Delta = \frac{L}{N(N-1)}$	L: Number of arcs N: Number of nodes			
Node Degree	$k_i \equiv \sum_{j\neq i} a_{ij}$	$a_{ij} \equiv \Theta\left[w'_{i,j}(t)\right]$	**Node Strength**	$s_i^i \equiv \sum_{j\neq i} w'_{ij} = \frac{s_i}{w_{tot}}$	$w'_{ij}(t) \equiv \frac{w_{ij}(t)}{w_{tot}(t)}$ $w_{tot}(t) \equiv \sum_i \sum_{j\neq i} w_{ij}(t)$
Outdegree	$k_i^{out} \equiv \sum_{j\neq i} a_{ji}$		**Outstrength**	$s_i^{out} \equiv \sum_{j\neq i} w'_{ij} = \frac{s_i^{out}}{w_{tot}}$	
Indegree	$k_i^{in} \equiv \sum_{j\neq i} a_{ij}$		**Instrength**	$s_i^{in} \equiv \sum_{j\neq i} w'_{ji} = \frac{s_i^{in}}{w_{tot}}$	
ANND in-in	$k_i^{in/in} \equiv \frac{\sum_{j\neq i} a_{ji} k_j^{in}}{k_i^{in}} = \frac{\sum_{j\neq i}\sum_{k\neq j} a_{ji} a_{kj}}{\sum_{j\neq i} a_{ji}}$		**ANNS in-in**	$s_i^{in/in} \equiv \frac{\sum_{j\neq i} a_{ji} s_j^{in}}{k_i^{in}} = \frac{\sum_{j\neq i}\sum_{k\neq j} a_{ji} w'_{kj}}{\sum_{j\neq i} a_{ji}}$	
ANND in-out	$k_i^{in/out} \equiv \frac{\sum_{j\neq i} a_{ji} k_j^{out}}{k_i^{in}} = \frac{\sum_{j\neq i}\sum_{k\neq j} a_{ji} a_{jk}}{\sum_{j\neq i} a_{ji}}$		**ANNS in-out**	$s_i^{in/out} \equiv \frac{\sum_{j\neq i} a_{ji} s_j^{out}}{k_i^{in}} = \frac{\sum_{j\neq i}\sum_{k\neq j} a_{ji} w'_{jk}}{\sum_{j\neq i} a_{ji}}$	
ANND out-in	$k_i^{out/in} \equiv \frac{\sum_{j\neq i} a_{ji} k_j^{in}}{k_i^{out}} = \frac{\sum_{j\neq i}\sum_{k\neq j} a_{ij} a_{kj}}{\sum_{j\neq i} a_{ij}}$		**ANNS out-in**	$s_i^{out/in} \equiv \frac{\sum_{j\neq i} a_{ji} s_j^{in}}{k_i^{out}} = \frac{\sum_{j\neq i}\sum_{k\neq j} a_{ij} w'_{kj}}{\sum_{j\neq i} a_{ij}}$	$w'_{ij}(t) \equiv \frac{w_{ij}(t)}{w_{tot}(t)}$; $w_{tot}(t) \equiv \sum_i \sum_{j\neq i} w_{ij}(t)$
ANND out-out	$k_i^{out/out} \equiv \frac{\sum_{j\neq i} a_{ij} k_j^{out}}{k_i^{out}} = \frac{\sum_{j\neq i}\sum_{k\neq j} a_{ij} a_{jk}}{\sum_{j\neq i} a_{ij}}$		**ANNS out-out**	$s_i^{out/out} \equiv \frac{\sum_{j\neq i} a_{ij} s_j^{out}}{k_i^{out}} = \frac{\sum_{j\neq i}\sum_{k\neq j} a_{ij} w'_{jk}}{\sum_{j\neq i} a_{ij}}$	
ANND tot-tot	$k_i^{tot/tot} \equiv \frac{\sum_{j\neq i} \left(a_{ij} + a_{ji}\right) k_j^{tot}}{k_i^{tot}}$	$k_i^{tot} \equiv k_i^{in} + k_i^{out}$	**ANNS tot-tot**	$s_i^{tot/tot} \equiv \frac{\sum_{j\neq i} \left(a_{ij} + a_{ji}\right) s_j^{out}}{k_i^{tot}}$	

A3. Definition of Topological Measures (cont.)

Binary Network			Weighted Network		
Index	**Definition**	**Parameters**	**Index**	**Expression**	**Parameters**
Network Centralization[28]	$C_D = \frac{\sum_{i=1}^{N}(k^* - k_i)}{(N-1)(N-2)}$	k^*: the largest observed degree	**WAND**	$WANND_i = \frac{\sum_j \sum_h w'_{ij} a_{jh}}{s_i}$	
Closeness Centrality	$CL_i = \frac{(N-1)}{\left[\sum_{i=1}^{N} d(i.j)\right]}$	$d(i,j)$:number of lines in the geodesic linking actors			
Betweenness Centrality	$RWBC_i = \frac{\sum_s \sum_{s \neq t} I_i(o,t)}{N(N-1)}$	o: node "source" t: node "target" $v(o,t)) = [D-A]^{-1} f(o,t)$ $D = diag(k)$ $[D\text{-}A]^{-1}$ computed using Moore-Penrose pseudo-inverse. f(o,t) the "source" NX1 vector such that $f_i(o,t)=1$ if i=o, $f_i(o,t)=-1$ if i=t; 0 otherwise. $I_i(o,t) = \left[\sum_j A_{ij} \lvert v_i(o,t) - (v_j(o,t)) \rvert\right]$	**Weighted Betweenness Centrality**	$RWWBC_i = \frac{\sum_s \sum_{s \neq t} I_i(o,t)}{N(N-1)}$	$v(o,t)) = [D-W]^{-1} f(o,t)$ $D = diag(s)$ $[D\text{-}W]^{-1}$ computed using Moore-Penrose pseudo-inverse. f(o,t) the "source" NX1 vector such that $f_i(o,t)=1$ if i=o, $f_i(o,t)=-1$ if i=t; 0 otherwise. $I_i(o,t) = \left[\sum_j W_{ij} \lvert v_i(o,t) - (v_j(o,t)) \rvert\right]$
Betweenness centralization	$\boldsymbol{BCN} = \frac{\sum_{i=1}^{N}[\boldsymbol{RWBC}(\boldsymbol{i}^*) - \boldsymbol{RWBC}(\boldsymbol{i})]}{(\boldsymbol{N}-1)}$	*BC*(i*): the largest realized actor RWBC index for the set of actors.			

[28] To calculate the group-level index of indegree or outdegree centralization, the denominator of expression is $(N\text{-}1)^2$.