Structural Change and Economic Dynamics 67 (2023) 98–114

Contents lists available at ScienceDirect

Structural Change and Economic Dynamics

journal homepage: www.elsevier.com/locate/strueco

Regionalisation and cross-region integration. Twin dynamics in the automotive international trade networks

Margherita Russo [a,#,*], Fabrizio Alboni [a], Jorge Carreto Sanginés [b], Manlio De Domenico [c], Giuseppe Mangioni [d], Simone Righi [e,#], Annamaria Simonazzi [f]

[a] *Department of Economics, University of Modena and Reggio Emilia, Modena, Italy*
[b] *Facultad de Economía, Universidad Nacional Autónoma de México, Mexico*
[c] *Department of Physics & Astronomy "Galileo Galilei", University of Padua, Italy*
[d] *Dipartimento di Ingegneria Elettrica, Elettronica e Informatica (DIEEI), University of Catania, Italy*
[e] *Department of Economics, Ca' Foscari University of Venice, Italy*
[f] *Sapienza University of Rome, Italy*

A R T I C L E   I N F O

JEL:
F14 empirical studies of trade
L62 automobiles
Other transportation equipment
Related parts and equipment
D85 network formation and analysis: Theory

Keywords:
International trade
Regional specialisation
Automotive components and parts
Dynamics of change
Infomap multilayer analysis

A B S T R A C T

The paper analyses the changes that occurred over 25 years in the geography of trade in automotive parts and components. Using the Infomap multilayer clustering algorithm, we identify clusters of countries and their specific trades in the automotive international trade network, we measure the relative importance of each cluster and the interconnections between them, and we analyse the contribution of countries and of trade of components and parts in the clusters. The analysis highlights the formation of denser and more hierarchical networks generated by Germany's trade relations with EU countries and by the US preferential trade agreements with Canada and Mexico, as well as the surge of China. While the relative importance of the main clusters and of some individual countries change significantly, connections between clusters increase over time.

1. Introduction

In recent years, the automotive industry is undergoing a paradigm shift that will affect the entire supply chain and has the potential to redraw the boundaries of the sector, redefine key players and sourcing practices, and impact the relative advantage of countries and regions, reshaping existing industrial geographies. In 2018, after 25 years of the North America Trade Agreement (NAFTA), the United States requested new rules which, among other things, increased the regional content in the production of automotive components and parts traded between the three partner countries, United States, Canada and Mexico (USMCA). Signed by all three countries, the new trade agreement went into force on July 2020 but its impact on the automotive industry is yet highly uncertain. Another significant shift in this industry – the accelerated rise of electric vehicles to cope with the increasingly stringent targets of CO2 emissions – also became apparent in 2020 when, upon reopening after the COVID-19 related closures, the tide was running against internal combustion engine vehicles, with all major car manufacturers announcing major investments in electric vehicles. Finally, after the Ukraine invasion in February 2022, an increasingly unpredictable global geopolitical context advises the reorganisation of value chains. All these changes also interact with one another, outlining re-shoring strategies of some OEMs (Original Equipment Manufacturers) to keep their level of employment in the core countries, to reduce the risk of disruptions, or to counteract the regional content rule, as in the case of electric vehicles produced in Mexico with Chinese batteries (Pavlínek, 2022; Russo et al., 2022; Schwabe, 2020a, 2020b).

The analysis of the ongoing transformations requires the identification of a benchmark of the configuration of the automotive industry before all these changes began. With an original analytical framework of

* Corresponding author.
E-mail address: margherita.russo@unimore.it (M. Russo).
CAPP Research Centre for the Analysis of Public Policies, University of Modena and Reggio Emilia, Italy.

https://doi.org/10.1016/j.strueco.2023.07.006
Received 1 August 2021; Received in revised form 1 July 2023; Accepted 10 July 2023
Available online 16 July 2023
0954-349X/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

bilateral trade networks, this paper contributes to building this benchmark by defining the changing configurations of automotive components trade networks in the three decades preceding the recent turmoil.

In the economic literature on international trade, the automotive global value chains have been studied through network analyses focusing on the centrality of geographical regions and countries, but largely overlooking the contribution of countries' bilateral trade in components in structuring the subnetworks of countries and their specific role in the overall trade network. We overcome this limitation using the Infomap multilayer clustering algorithm (Rosvall and Bergstrom, 2008; De Domenico et al., 2015) on the UN Comtrade database (https://comtrade.un.org/data) of directed export and import flows, comprising 30 automotive components and parts among 42 countries (accounting for 98% of world trade flows of those items). This approach allows us to identify meso-scale entities, operationalized as clusters of countries, and their specific trades in the automotive international trade network. Further, this enables us to highlight – in their evolution over a period of 25 years - the relative importance of each cluster and the interconnections between them, as well as to analyse the contribution of countries and of components and parts in the clusters.

Thanks to the use of multilayer network models in detecting meso-scale entities, we address three issues. First, we identify the clusters of countries that define the trade networks without referring to conventional geographical areas but rather leveraging the pattern of recurring interactions in countries' bilateral trade flows in the various components. Second, we evaluate the contribution of countries and automotive components in determining the relative importance and structure of the various clusters over time. Third, we analyse the changes in the relative positions of countries within and across clusters and in their specialisations in multilateral exchanges. Specifically, the paper highlights the changes that occurred between 1993 and 2017 in the geography of trade relations, with particular regard to denser and more hierarchical networks generated by Germany's trade relations with the EU countries and the US preferential trade agreement with Canada and Mexico, as well as the upsurge of China. With a similar overall variety of traded components and parts within the main clusters (dominated respectively by Germany, US and China&Japan), the Infomap multilayer analysis singles out which components and parts determined the relative positions of countries in the various clusters and the changes over time in the relative positions of countries and their specialisations in multilateral trades. Countries' relative position in international trade depends on various dimensions, including a country's skills and competences, the position of its companies in the automotive supply chain, its industrial policies, the preferential trade agreements to which it is party. These dimensions determine the direction and size of trade flows, that are the focus of our analysis, and will be considered in interpreting the results.

The paper is structured as follows. To contextualize the method of analysis proposed in this paper, Section 2 surveys the literature on network analysis of international trade and highlights major results so far obtained and the gaps that we try to fill with our analysis. Section 3 presents the data sources. Section 4 describes the analytical model methodology of Infomap multilayer cluster detection adopted in our analysis (details on the mathematical model and parameters' setting used in the implementation of the algorithm are in Annex). Section 5 illustrates the results of the analytical model: the meso-scale entities detected by the algorithm and the pattern of twin dynamic of regionalization and cross-region integration. Section 6 builds on these results to focus on trade patterns - by cluster of countries, countries and products - and on the implications of environmental regulations on trade of internal combustion engine (ICE) components, which will be displaced by 2035 when EU, China and US will enforce more stringent norms for sustainable vehicles. Section 7 discusses the results and concludes with an outlook on further research directions this research opens up[1].

2. Issues in the network analysis of automotive trade of components and parts

The automotive industry is highly concentrated, with the top 20 automakers employing approximately 75% of all the sector's workforce and contributing about 88% of the global vehicle production volume in 2018 (Hoeft, 2020)[2]. While traditionally highly clustered in core areas, since the late 20th century this sector has embraced global sourcing, with peripheral areas taking on more prominence due to the profit-seeking strategies of producers seeking to exploit countries' differences in levels of development and factor costs (Harvey, 2014). The reorganisation of the automotive supplier industry, even in presence of governments' restrictions to trades, was made possible by technological and organisational changes that significantly reduced the number of suppliers and organised the remaining ones into tiers (Sturgeon et al., 2008; Womack et al., 1991). The requirements of just-in-time production, alongside constraints on regional value content in the US trade agreement with Canada and Mexico and the common request by OEMs to their main suppliers to be followed in their new locations (the so called "follow sourcing"), led to the increased clustering of especially Tier-1 suppliers around assembly plants (Pavlínek, 2018), with local, regional and national value chains nested within the global organisational structures and business relationships of the largest firms (Sturgeon et al., 2008: 304). The need to produce where you sell added to the production diaspora. The geographic structure of the automotive industry is now based on the presence of large assemblers and leading (global) suppliers in all major markets, organised in functionally integrated macro-regional production networks. The competitive process results in the dynamic nature of countries' positions within automotive production networks, with production (and trade) moving from countries that originally were at the centre of the automotive production (US, Germany, Japan) to a larger group of countries that were becoming integrated with the original ones in various configurations of dependency, structured by patterns of specialisation and integration in regional areas (Amighini and Gorgoni, 2014; Celi et al., 2018; Gorgoni et al., 2018; Klier and Rubenstein, 2008; Pavlínek, 2018, 2020, 2022; Sturgeon et al., 2008; Womack et al., 1991).

The fragmentation of production in global value chains and the emergence of regional specialisations have prompted the flourishing of a rich literature using network analysis, as trade data fit perfectly this methodology thanks to the availability of yearly official (e.g. from United Nations) datasets for all countries covering long time-spans with highly detailed commodity specification. A network approach is proposed to analyse and compare weighted trade networks over time, to focus on global value chains, to interpret the specific features characterising international trade (product complexity, centralized network). A selected group of contributions is examined in this Section describing their methods and results to highlight specific gaps that we overcome with the specific methodology proposed in our paper.

To characterise the dynamics of international trade, the seminal paper by Fagiolo et al. (2009) studies the topological properties of world trade by focusing on distribution dynamics and evolution. More specifically, they employ a weighted network approach to characterise, for

[1] Selected Figures and Tables marked with the symbol can be browsed online - by using the tool implemented with Tableau Public - with respect to data and community detection (part A), and to flows within and between clusters (part B). Changes over time in the relative positions of countries and their specialisations in multilateral trades can be explored in detail.

[2] Annex 1 presents figures on the share of production of vehicles by country (Fig. A1) and by car maker (Fig. A2) in the years 2003, 2013 and 2017 and export and imports of automotive components and parts and of motor cars (Table A1).

the period 1981–2000, the distribution of the most important network statistics: node connectivity, assortativity, clustering, and centrality, as well as link weights. The paper leads the way for various contributions using network analyses for assessing the distributional properties of these statistics (and their correlation structure), their predictive implications, and the impact of the adoption of alternative -economically meaningful -weighting schemes on the results.

In line with the exploration of topological properties of world trade, Barigozzi et al. (2011) conceptualise international trade in a multiplex framework[3], where each category of commodities is considered as a separate international trade network. Bilateral trade flows for 97 products (from UN Comtrade statistics, 2-digit Harmonized System 1996 classification) refer to a panel of 162 countries for which data is available over the period 1992–2003. The analytical perspective adopted by Barigozzi et al. (2011) allows for comparison across the different cluster configurations in which countries are embedded in specific trades, and shows the heterogeneity of commodity-specific community structures and that their statistical properties are quite different from those of the community structure of the aggregate network. The results of this paper are very important to address our empirical research issue, but the level of aggregation adopted in their analysis encompasses automotive components and parts in the single item "Vehicles (not railway, tramway, rolling stock); parts and accessories" and thus their results are not comparable with the ones obtained in our analysis.

With a focus on the similarity of global value chains (GVCs), Zhu et al. (2018) provide a new method to measure cross country similarities in the various GVCs, over time. They use the World Input–Output Database (WIOD) to construct both the upstream and the downstream global value networks. Their original method takes into account a crucial feature in comparing the various GVCs, i.e. the specialisation of countries in products that are absorbed in different proportions by domestic and export markets. Although central in the assessment of the relative position of countries in the GVCs, as in Barigozzi et al. (2011), the level of aggregation – in this case 35 sectors (from mining to services) in the WIOD - does not allow to focus on automotive components and parts, all-in-all in the "Transport equipment".

In order to describe changes in the overall structure of trade, another approach studies network components (subnetworks) and their density (see Fortunato and Hric, 2016, for a survey of theoretical contributions). In this strand of literature, Piccardi and Tajoli (2018) analyse network structures to interpret the specific features characterising international trade (product complexity, centralized network). Using data from the CEPII-BACI database, inter-country trade of 223 countries for 1242 products (HS 4-digit classification), they define a weighted, directed network for each product and compare their results with respect to the products' complexity, which they refer to three measures (overall strongly positively correlated): the Hausmann-Hidalgo Index (Hausmann et al., 2011), the Fitness Index (Tacchella et al., 2012) and the weighted average income per-capita of the exporting country (Hausmann et al., 2007). They conclude that the "trade networks that are more centralised are those that have more complex products". Although very focused on essential characteristics of the various subnetworks (i.e. the complexity of the traded products), this paper does not shed light on the empirical contributions of countries and specific products in shaping the subnetworks, which are one of the results of the present paper. Nonetheless, in a further development of our research project our results could be complemented with the same measures of product complexity they compute in their paper. This would allow to take into account - in the cross country specialisation in the automotive GVC - the background of competences that is embedded in the notion of product complexity.

[3] Arenas and De Domenico (2016) note that, historically, the term multiplex was coined to indicate the presence of more than one relationship between the same actors of a social network. The terms 'multiplex' and 'multilayer' are used almost indistinctly as they fundamentally refer to the same concept.

With a focus on the changing international structure of the automotive trade, Amighini and Gorgoni (2014) obtain results consistent with the literature stressing the regionalisation of production (Freyssenet et al., 2003; Klier and Rubenstein, 2008). They implement a network analysis to assess: (a) the impact of the rise of new supplying countries on the organisation of auto production and the geography of suppliers; (b) the contrasting tendencies towards globalisation and regionalisation of production. Both questions are close to the empirical issues addressed in our paper, but their method has some limitations with respect to concepts of regionalisation and globalisation. They use directed weighted shares of trade flows, in 1993 and 2003, of four groups of products that encompass 30 automotive components and parts. Aggregation in the four groups, instead of using individual components, is justified by Amighini and Gorgoni by the relative technological homogeneity within those groups, respectively: engines; rubber and metal parts; electrical and electric parts; and miscellaneous parts production. Their hypothesis is that fragmentation of production networks is largely driven by technological content and value-to-weight ratios (Hummels, 2007). Adopting a mutually exclusive geographical partition of countries in regional groups (Western Europe, Eastern Europe, North America, Latina America, Asia, and Oceania), Amighini and Gorgoni use an homophily measure called E-I index (McPherson et al., 2001) to assess the degree of regionalisation of each valued network. Implementing the classification of brokerage roles proposed by Gould and Fernandez (1989) on the four networks (computed for 1993 and 2003), the authors are able to assess the various brokerage roles of the various countries, within and between regional groups. The result of this analytical model is the emergence of an increasingly hierarchical specialisation, with regionalisation of production still dominating the auto industry and fewer countries accounting for most of the world trade, in particular in the case of electrical and electric parts and miscellaneous parts that show more hierarchical networks, interpreted as the increasing concentration in a few countries of trade flows of components with higher technological content. The countries composing the core change over time. Engine parts networks became more globalised, but still more regional than global.

Focusing on a similar issue and based on the same methodology, in a more recent paper, Gorgoni et al. (2018), implement the same brokerage measures on three years (1993, 2003 and 2013) referring in this paper on the same set of countries (and not on different set according the group of products under exam as in Amighini and Gorgoni, 2014), but refer only on three out of four the previous examined groups of automotive products, excluding the miscellaneous group. Their results confirm what previously observed, with a new result on the role played by China entering the core in 2013 and the Czech Republic and Poland becoming central in Europe.

The current network literature does not capture meso-scale entities (cluster of countries) as emerging properties of cross country trades across the many interrelated trades of component and parts. To overcome the limits of current trade network literature and to address the analysis of the complex networks generated by trade, in this paper we focus on detection of multilayer meso-level entities.

Even though the contributions of Piccardi and Tajoli (2018) is in line with the identification of subnetworks within a network, and is functional in discussing the regionalization characteristics of trade networks, this contribution fails to address the more complex features of such networks that derive from multiple types of interactions, measured by bilateral trade flows occurring over time among countries, with different overall volumes of trade and specific bilateral trade. Analysis of multilayer clustering yields evidence to create a better understanding of features characterising those subnetworks, but specific methods need to be adopted to identify the recurring patterns of countries' trade across the various items under analysis, rather than considering each group of items separately.

Amighini and Gorgoni (2014) and Gorgoni et al. (2018) have a different focus, i.e., countries' centrality measures. Although relevant for ranking countries, the centrality measures do not provide information about the multilayer meso-level entities determined by the relative positions of the countries in the various trade flows. Their contributions overlook the fact that meso-scale entities of complex networks cannot be solely disentangled by categorical partitions, such as grouping the countries according to their geographical position and grouping components and parts according to their relative technological homogeneity. As we observe in our analysis, results go in a different direction when the model relax their assumptions on predefined regional groups of countries and predefined grouping of products and relies on an algorithm of community detection.

With our analysis we aim to identify the changes in the topology of international trade in the automotive global value chains in the period 1993–2017, comparing the configuration of international trade networks (exports and imports) in the years 1993, 2003, 2013 and 2017. In particular, our aim is to identify the groups of countries and the components and parts around which the networks of relations are structured and how they change over time.

Our analytical model of trade multilayer networks allows to conceptualise the notions of "regionalisation" and "globalisation" as emergent properties of the clusters of countries and trades identified in the world trade network, and not as *a priori* attributions of countries in their geographical position, highlighting the relative importance of the clusters of countries and of individual countries over time.

Countries' position in international trade depends on various dimensions, including skills and competences within the country (Hausmann et al., 2011), the position of its companies in the automotive supply chain, and the preferential trade agreements to which the country is a member. The country's set of skills, wages, regulations, innovation ecosystems and absorptive capacity shape the structure of supply of automotive components and parts, which also depends on other production specialisations in the country, as well as the location of domestic and foreign car makers' plants in the country, and on the role assigned by carmakers to supply from that country with respect to their global supply chains. Supply of components and parts, in fact, is embedded in the relationships between carmakers, with their different ramifications for assembly plants in the various final markets and their networks of supplier companies in the various countries. Regional trade agreements affect the centrality of countries by stimulating demand in specific trade and promoting changes in technologies and the organisation of industries. These dimensions, that determine the direction and size of trade flows, do not enter into the analysis of data at country level but are considered in interpreting the results.

3. Data

3.1. Automotive components and parts: selection criteria and data source

Within the context of the Standard International Trade Classification Revision 3 (SITC Rev. 3), no 2- or 3-digit aggregate would fit an analysis focusing on the set of components and parts specifically traded in the automotive global value chains (see Annex 2 for details). Thus, we chose to adopt the same list of trade items used in the previous literature. In particular, we adopt the same list of 30 SITC Rev.3 items proposed by Amighini and Gorgoni (2014), leveraging their careful selection which largely avoids the inclusion of components and parts not belonging to the automotive industry[4]. These items, listed in Table 1, were grouped into four main categories: Electrical and Electric Parts, Rubber and Metal Parts, Engines and Parts, Miscellaneous Parts.

The data source is the UN Comtrade International Trade Statistics Database. Under analysis is the set of (gross) bilateral export and import flows in 1993, 2003, 2013 and 2017. These years allow a comparison of the impact of NAFTA (signed in 1992) after 10 and 20 years, and the latest year available for data analysis; and will constitute a benchmark for a pre-post assessment of the geography of production due to the net zero emission target of the EU and USA regulations. For those years, three-year average data are considered (the year under analysis, the year before and the following year). For each year and for each flow (import and export[5]) shares of trade flows of the various components and parts are computed. We focus on the trade relations of the top 42 reporting countries[6] with all the countries in the UN Comtrade database. The remaining countries represent tiny fractions of the global trade both individually and as a group. Indeed, the 42 countries represent, respectively, in 1993 and 2017, 98.1% and 97.1% of the total exports of those 30 SITC items (details in Annex 3).

3.2. Data description

In terms of export shares (Table 1), the biggest and most heterogeneous group is Miscellaneous Parts, comprising a slightly increasing share of almost two thirds of trade. In 1993, the main items - respectively, almost 35% and 11% of total trade - refer to "other parts and accessories" (classified, respectively, in SITC 78439[7] and 78432); the group Engines and Parts accounted for almost 19% of trade, the main item being "Internal Combustion Engines"; Rubber and Metal Parts, with 9.3% of trade, which decreases in 2003. Electrical and electronic parts have a similar share over the 25 years, with the share of Electric Accumulators (storage batteries) increasing to almost 6% of total trade, while Sealed-beam Lamp Units fell to one third.

An analysis of export shares by year and country (Fig. 1, top panel) shows a substantial change in the relative importance of the various countries. In 1993, the first five exporters of automotive components and parts - Japan, US, Germany, France and Canada – accounted for 67.3% of total exports, down to 44.8% in 2017 (only Germany managed to maintain its share). Conversely, China, Mexico, South Korea, and the Central and Eastern European (CEE) countries increased their overall share from 7% in 1993 to 33,5% by 2017. The big shift occurred between 1993 and 2003; thereafter, China and Mexico consolidated their increasing importance, while the US continued its decline.

Turning to imports, Fig. 1 (bottom panel) highlights the marked imbalances in Japan's trade, while a comparison with Germany suggests a different response by the companies of the two countries to the challenges of globalisation (Celi et al., 2018; Hufbauer and Jung, 2021; Simonazzi et al., 2022; Sturgeon et al., 2008; Womack et al., 1991). The US maintained considerable (though slightly declining) importance as an importing country, while Canada's poor performance (declining shares of both exports and imports) suggests a progressive

[4] According to Amighini and Gorgoni (2014, Annex Table A1 Auto Parts Classification pp. 944–45), such "classification is partly similar to the parts product listings adopted by the US Office of Aerospace and Automotive Industries (OAAI) ... [and] attempts to closely approximate the core automotive industry by excluding certain items for example, parts explicitly listed for motorcycles, golf carts, snowmobiles, agricultural equipment, etc." (ibid., footnote 5).

[5] With regard to export flows, as in Gorgoni et al. (2018), "data are tabulated using importer records, more reliable than the corresponding exporter records".

[6] The 42 countries are: Argentina, Australia, Austria, Belarus, Belgium, Benelux Union (Belgium, the Netherlands, and Luxembourg), Brazil, Canada, China, Czech Republic, Denmark, Finland, France, Germany, Hong Kong, Hungary, India, Indonesia, Ireland, Italy, Japan, Malaysia, Mexico, Netherlands, Philippines, Poland, Portugal, Romania, Russia, Singapore, Slovakia, Slovenia, South Africa, South Korea, Spain, Sweden, Switzerland, Thailand, Turkey, UAE, UK, Ukraine, US. The 1993 data (1992–1994) data refer to Belgium-Luxembourg, while for the following years there are only the data for Belgium. Thus, there are 42 countries in total (Luxemburg never appears in the list). Details of the list of countries in Annex 3.

[7] See Annex 2, Table A3 for the list of products included in the item 784.39 (SITC Rev.3) "other parts and accessories of the motor vehicles of groups 722, 781, 782", which are, respectively: 722: Tractors (excluding those of 71414 & 74415); 781: Motor vehicles for the transport of person; 782: Motor vehicles for transport of goods, special purposes.

Table 1
List of automotive components and parts, by group, and their share of export, in the years 1993, 2003, 2013, 2017.

group description	SITC & description	year 1993	2003	2013	2017
Rubber and Metal Parts	6251_Tyres, pneumatic, new, of a kind used on motor cars (including station wagons and racing cars)	6.47	5.31	6.95	5.86
	62551_Tyres, pneumatic, new, other, having a herring-bone or similar tread	0.56	0.43	0.66	0.44
	62559_Tyres, pneumatic, new, other	0.62	0.46	1.11	0.73
	62591_Inner tubes	0.30	0.12	0.13	0.10
	62592_Retreaded tyres	0.16	0.08	0.09	0.09
	62593_Used pneumatic tyres	0.19	0.08	0.08	0.05
	62594_Solid or cushion tyres, interchangeable tyre treads and tyre flaps	0.16	0.12	0.18	0.13
	69915_Other mountings, fittings and similar articles suitable for motor vehicle	0.77	1.12	1.00	1.11
	69961_Anchors, grapnels and parts thereof, of iron or steel	0.04	0.03	0.04	0.03
Electrical and Electric Parts	76211_Receivers, radio-broadcast, not capable of operating without an external source of power...incorporating sound-recording or reproducing apparatus	3.69	3.15	1.69	1.20
	76212_Receivers, radio-broadcast, not capable of operating without an external source of power...not incorporating sound-recording or reproducing apparatus	0.45	0.24	0.16	0.21
	77812_Electric accumulators (storage batteries)	3.04	3.89	4.81	5.76
	77823_Sealed-beam lamp units	0.19	0.13	0.10	0.06
Engines and Parts	71321_Reciprocating internal combustion piston engines for propelling vehicles, of a cylinder capacity not exceeding 1000 cc	0.78	0.42	0.37	0.38
	71322_Reciprocating internal combustion piston engines for propelling vehicles, of a cylinder capacity exceeding 1000 cc	8.86	8.56	6.13	5.72
	71323_Compression-ignition internal combustion piston engines (diesel or semi-diesel)	3.88	4.94	5.84	5.35
	77831_Electrical ignition or starting equipment of a kind used for spark- ignition or compression-ignition internal combustion engines	2.84	2.41	2.76	2.72
	77833_Parts of the equipment of heading 778.31	0.77	0.68	0.56	0.57
	77834_Electrical lighting or signalling equipment (excluding articles of subgroup 778.2)	1.70	1.77	2.78	3.50
Miscellaneous Parts	7841_Chassis fitted with engines, for the motor vehicles of groups 722, 781, 782 and 783	1.57	0.91	0.49	0.43
	78421_Bodies (including cabs), for the motor vehicles of group 781	0.28	0.63	1.11	0.88
	78425_Bodies (including cabs), for the motor vehicles of groups 722, 782 and 783	0.86	1.02	0.77	0.79
	78431_Bumpers and parts thereof, of the motor vehicles of groups 722, 781, 782 and 783	1.11	0.90	1.01	1.13
	78432_Other parts and accessories of bodies (including cabs), of the motor vehicles of groups 722, 781, 782 and 783	10.66	13.70	12.23	12.50
	78433_Brakes and servo-brakes and parts thereof, of the motor vehicles of groups 722, 781, 782 and 783	4.91	5.24	5.01	4.90
	78434_Gearboxes of the motor vehicles of groups 722, 781, 782 and 783	6.96	7.29	10.58	10.55
	78435_Drive-axles with differential, whether or not provided with other transmission components	1.73	1.62	3.82	3.58
	78436_Non-driving axles and parts thereof, of the motor vehicles of groups 722, 781, 782 and 783	1.07	1.17	0.00	0.00
	78439_Other parts and accessories, of the motor vehicles of groups 722, 781, 782 and 783	34.87	33.06	29.10	30.83
	82112_Seats of a kind used for motor vehicles	0.51	0.49	0.44	0.41

marginalization of the country, to the advantage of Mexico. As largely discussed in the literature (Sturgeon et al., 2008; Womack et al., 1991), since the 1980s, Japanese OEMs practiced an original model of integration with their suppliers largely located very close to their assembly plants, to enhance the just-in- time feature of their lean production model. This explains the very modest quantity of imports of components and explains why their exports decline progressively with the expansion of their investment in assembly plants abroad, together with their network of suppliers that became located nearby (refer to Sturgeon et al. 2008, pp. 308–309, 311–15), an issue that we discuss in the next paragraph. A different production model, and a peculiar geopolitical context, is the one of China (Schwabe, 2020b).

3.3. Network of countries' bilateral trade flows

The changes in the relative position of countries in their network configurations are illustrated in Fig. 2. The size of the nodes is proportional to the country's share of exports with slices proportional to shares of export and import of vehicles (respectively, dark green and light green) and export and import of components and parts (respectively, red and orange) out of the total country's trade exchange. The thickness of the link between countries is proportional to their trade flow, compared to the maximum share over the four years. It should be noted that for each year, export and import flows between two countries have the same thickness, but opposite direction.

The graphs highlight a clear structure of subnetworks of trade flows with an evident geographical base: one subnetwork centred in Europe, on the left in each graph, another in the Pacific area (embracing countries in East Asia, the US and Canada), on the right in each graph. The change in the positions of Japan and Germany relative to the United States on the one hand, and the inversion in the relative positions of Mexico and Canada in their trade with the US on the other, are explained by the different strategies of car manufacturers targeting the US market. In the 1970s–80s, US companies had to respond to the increasing foreign (mainly Japanese) competition in their own, hitherto protected, market. The Japanese threat threw the US auto industry into panic and triggered the US government's response. The protection of the domestic market from import penetration attracted foreign direct investment. Japanese TNCs brought Tier 1 suppliers with them, but they also instructed US parts suppliers on better manufacturing and quality control methods, and component manufacturing was upgraded. Exports were partially replaced by local production. Faced with the risk of losing control of their home market to foreign manufacturers, US carmakers resorted, among other strategies, to offshoring of labour-intensive operations, relocation to the Southern non-unionised states in the US and delocalisation of assembly plants to Mexico, even before the NAFTA was signed. The creation of a North American free trade area attracted FDI to Mexico (the cheapest location) to export to the US. Thus, over the two decades, OEMs moved their assembly plants to the United States and, subsequently to Mexico, becoming a source of demand for components and parts for their supply chains, thus inverting the relative positions of Mexico and Canada in their trade with the US.

In the case of Europe, since the 1990s - following the fall of the iron curtain first, and then the Eastern enlargement of the European Union - massive relocation of production eastward has allowed the main European OEMs, and especially the German ones, to take advantage of the creation of the Common Market and meet the challenges represented by Japanese and, later on, Korean TNCs (Brincks et al., 2018). Unlike in the

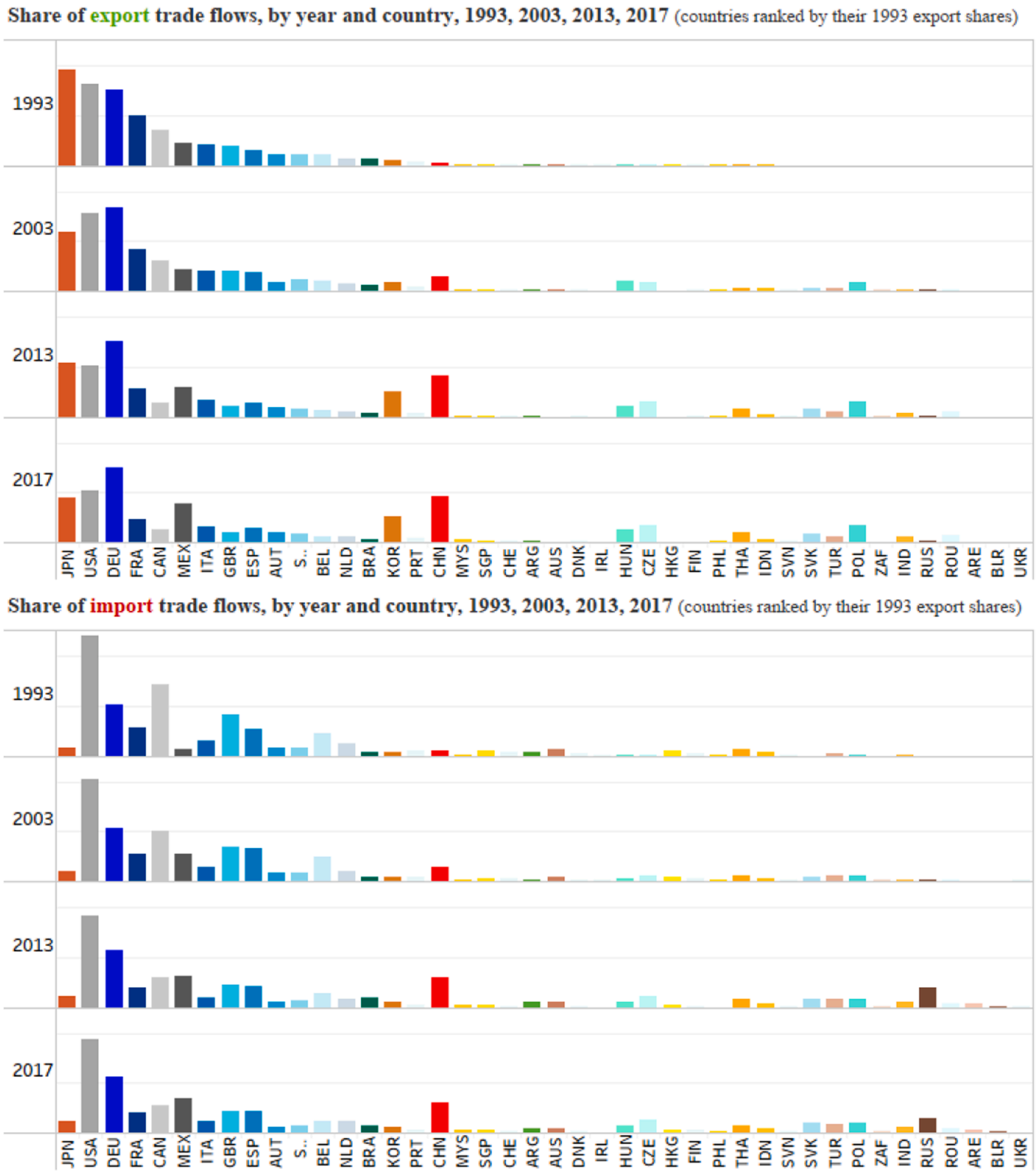

Fig. 1. Export and import shares by country in 1993, 2013, 2003 and 2017.

US, however, these processes contributed to reinforcing the competitive position of the lead country and its 'national champions'. In fact, compared to the US, German companies offshored a higher share of components and small cars, while retaining at home a higher share of production and assembly of premium cars (Simonazzi et al., 2020). Therefore, although production plants in Europe and North America have increasingly been located in peripheral regions - Mexico in North America and former communist countries in Europe - the consequences on the composition of trade (as well as on production and employment) have been substantially different (Simonazzi et al., 2022).

Finally, China's impressive rise in relative importance is justified by its entry into the WTO in 2001, its thriving domestic market, as well as its policy of attracting FDI to create a domestic auto industry. Although comprehensive, this analysis leaves the role and relationship among the different groups of countries undefined: to identify such multilayer meso-level entities, emerging in the trade flows, we use the Infomap multilayer methodology which we will describe in detail in Section 4.

4. Methods: multilayer network analysis

4.1. A multilayer method for module detection

As noted in the previous section, the international trade of automotive components can be conceptualized as a network where countries constitute nodes and trade relations are ties between these nodes. For example, in the trade network that we analyse, we may focus on a pair of bilateral trade flows, such as the one between two countries like US and Mexico, where both countries have import and export of the same product, e.g. *SITC code 78433 - Brakes and servo-brakes and parts thereof, of the motor vehicles of group*: we may expect that this specific bilateral trade corresponds to products of different quality or characteristics in the same category of classification. Taking into account cross country

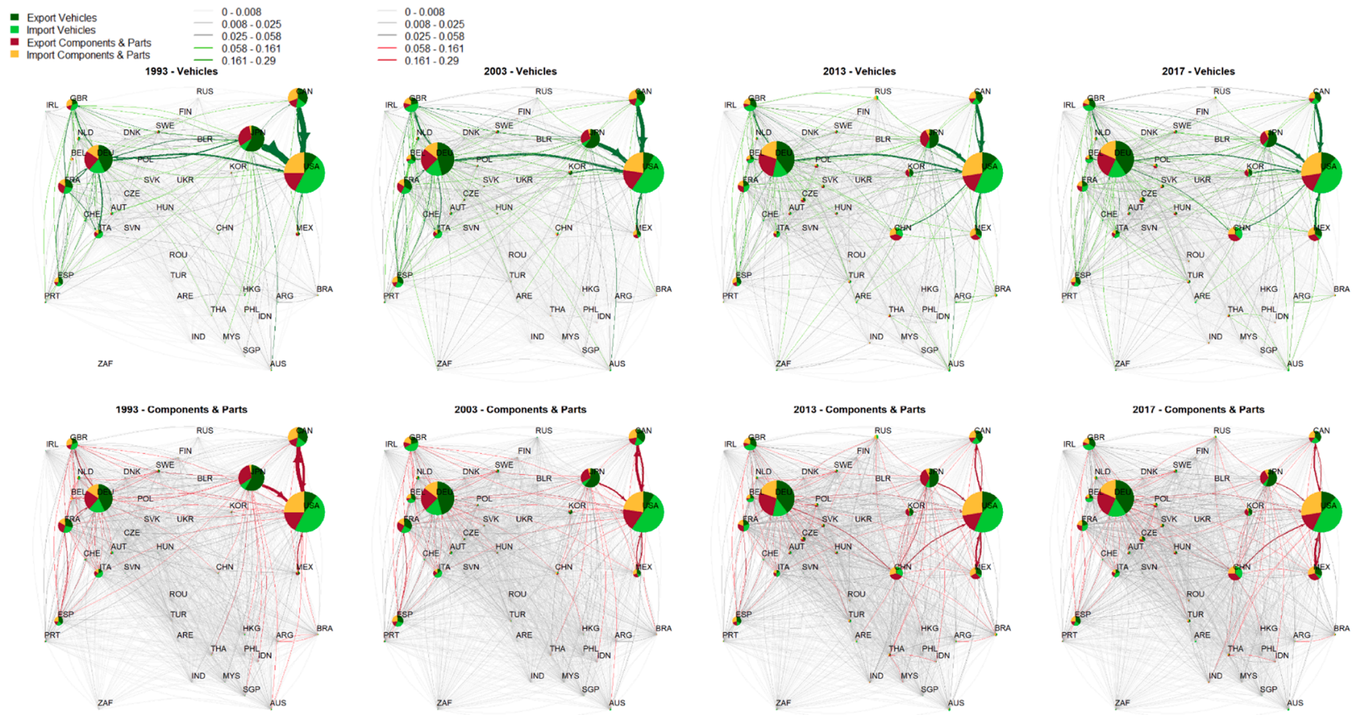

Fig. 2. Bilateral export and import trade of vehicles (SITC Rev.3: 781) and automotive components and parts (30 items, SITC Rev.3), in 1993, 2003, 2013 and 2017, 42 countries

NODES [countries] approximation of relative geographical position in the graph; *size* proportional to the total share of trade exchange (export + import) in the year; *slices*: shares of export and import of vehicles (respectively, dark green and light green) and export and import of components and parts (respectively, red and orange) out of the total country's trade exchange; *EDGES* [bilateral trade flows, top panel: vehicles, bottom panel: components and parts]: *thickness* proportional to trade share, compared to the maximum share over the four years; *colour of edges*: 5 classes based on the distribution of shares for all years. Arrows indicate the direction of export flows.

bilateral trade exchanges over all the 30 automotive components and parts contributes in profiling the specific relative position of countries in the overall network. While dyadic patterns are important in identifying the relative role of countries, identifying groups of countries can provide a much richer picture of the power, importance and evolution of countries in their networks.

Over time, many algorithms have been proposed to identify cohesive subgroups of nodes as clusters (or modules) within networks (prominently, Blondel et al., 2008; Fortunato and Hric, 2016; Girvan and Newman, 2002). Classical network models, however, do not take account of the complexity exhibited by systems in which multiple levels of descriptions are required to preserve microscopic information on interactions of different types - in our trade network: all the cross country bilateral trade exchanges over the 30 products – that evolve over time.

Instead of examining separately and then comparing the trade networks of each product (as in Barigozzi et al., 2011; Piccardi and Tajoli, 2018) or groups of products (as in Amighini and Gorgoni, 2014, or Gorgoni et al., 2018), to this end, it is expedient to use more sophisticated models such as multilayer networks, which are able to take into account the additional levels of complexity (Boccaletti et al., 2014; De Domenico et al., 2013; Kivela et al., 2014). In this class of models, a pair of nodes can be related by one or more types of interactions or relationships. Each interaction type (in our case: directed weighted trade flow, i.e., value of import or export, for each product) is mapped into a 'layer' of description. A layer collects all the pairwise interactions of the same type. Within each layer, nodes (i.e. countries) are usually referred to as 'state-nodes' (for example: when we consider - for any given year - export of the US to the other 41 countries, in the layer "brakes" we are considering the state-node "US-exporting brakes, in that year"). Connections between state-nodes define intra-layer connectivity (for example, all the bilateral trade flows of brakes, in a given year). The set of all state-nodes corresponding to the same node defines their physical node (i.e., the total export, or import, of a country in a given year). Connections between state-nodes of the same physical nodes, or between state-nodes of distinct physical nodes, define inter-layer connectivity, which plays an important role in shaping the collective phenomena emerging from the dynamics in the system (De Domenico et al., 2016)[8].

Data presented in Section 3 are mapped in the multilayer model. Each country in our dataset constitutes a physical node and every layer studies trade relationships (separately for import and export) of a category of components. To obtain the most effective estimations, the trade data will be considered at the most disaggregated level available in trade statistics. In particular, we consider 60 layers (30 components and parts, by import and export) for each of the four years, and for each of the 42 nodes (the countries)[9].

We use the Infomap multilayer algorithm of module detection (Rosvall and Bergstrom, 2008; De Domenico et al., 2015) to identify meso-structures (hereafter clusters) that are intermediate between the network as a whole and the individual countries (nodes) that have trade relationships with other countries. We refer the reader to Annex 4 for a more technical description of the algorithm.

It should be noted that the level of economic complexity (Hidalgo,

[8] Figure in Annex 11 schematises the example of countries in the multi-layer framework and highlights nodes and state-nodes.

[9] For some countries, trade flows do not cover all the SITC codes in all the years. The weights adopted in the analysis, the structure of the .net file, and optimal relax rate for the multilayer algorithm are presented in Annex 4.

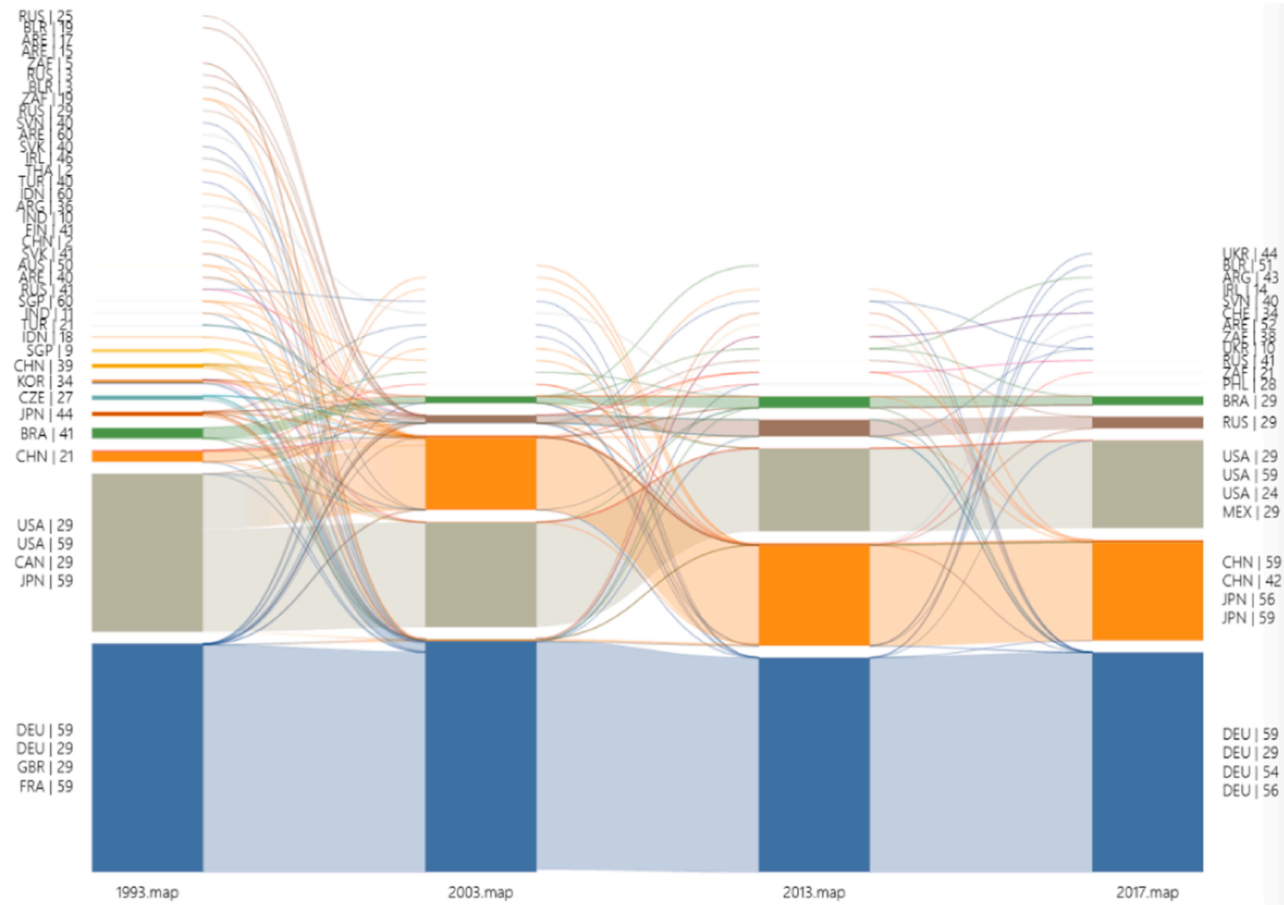

Fig. 3. Clusters of countries trade exchanges: alluvial, 1993–2017.
Clusters are lined up in columns, by each year. Size of cluster proportional to the Infomap flow. Labels on the left side (1993) and on the right side (2017) refer to the top combinations country and layer (at most four are shown i). Colours refer to the ID of the cluster and are associated with the top country-and-layer. Colours of clusters with a very low Infomap flow may not be visible and are just in white. Clusters are ranked by their value of Infomap flow.

2021) discussed in this manuscript refers to the multi-layer analysis of the automotive world trade. More complex economies tend to be more embedded in the international trade of various classes of components while less complex ones will have more specialized roles in the trade multi-layer network (e.g. by being active in few layers or by being pure importers/exporters of fewer categories of goods). In this sense, the level of embeddedness of a country in the overall network reflects the degree of economic complexity of the automotive sector in a country.

4.2. The multilayer model of international trade over time

The algorithm is designed to identify multilayer meso-level entities, in our case clusters of countries and their specific trades, for each year. However, the flow used to compute the modules provides also a metric to assess the relative importance of the clusters detected and the contribution of the individual countries and their links (weighted bilateral trade) in determining those clusters. Indeed, the algorithm normalises trade flows, occurring within layers and between layers, in an index (Infomap flow) ranging from 0 to 1. Thus, aggregating flows within and across layers (i.e. classes of components and parts for the automotive industry) and modules (i.e., groups of combinations of countries and components/part) makes it possible to identify the key clusters, how (and how strongly) they relate to each other, and where their key components come from (i.e. from which layers).

5. Results: clusters of automotive trade and their determinant over time

The Infomap multilayer algorithm identifies clusters of countries in the world trade of automotive components and parts and permits decomposing the flow, in terms of the underlying layers (components and parts) and nodes (countries), within and between the detected clusters of countries, thus identifying the building blocks to answer our research questions[10]. In this Section, we interpret the results on clusters of automotive trade detected by the Infomap algorithm, and we assess the connections between clusters of countries in terms of the countries' specific trade across clusters.

5.1. Meso-scale entities, by year

In contrast with geographical clustering, where each country has a unique position in the trade network, the clusters identified using the

[10] Infomap flow is decomposable by node (the countries), by layer (the SITC codes for the export and import trades) and by flow from state-node to state-node (which represent the random walk paths along the countries' bilateral trade of a specific component), thus providing information on each of the determinants of the detected clusters. See Annex 5 with the details on the Infomap output files analysed in this section. To visualize a random walker path see https://www.mapequation.org/apps/multilayer-network/index.html

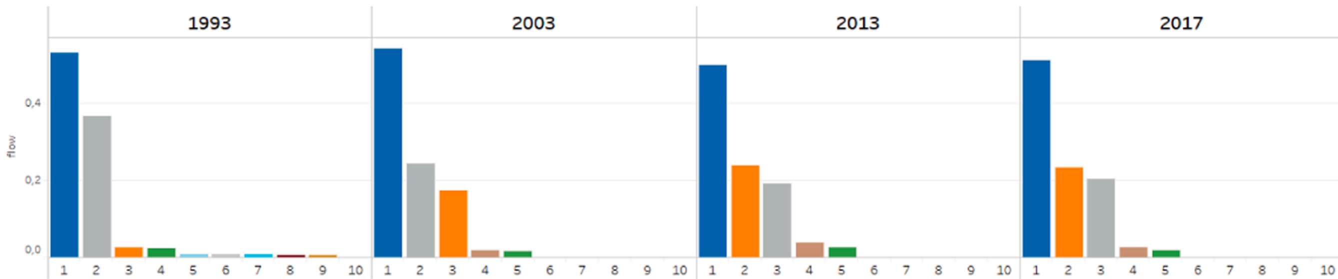

Fig. 4. – Infomap flow by cluster.
Only the first ten clusters in terms of Infomap flow, accounting for 97% of the total flow, are displayed.

Infomap multilayer algorithm must be interpreted keeping in mind two general aspects deriving from the algorithm itself. First, a country might belong to more than one cluster, according to the specific bilateral trade in which it is involved. Second, when we compare clusters over time, we consider the countries and specific trade characterising them, and we assign a label and colour to facilitate such a comparison, but we should not forget that the internal composition of each cluster in terms of countries and trade could change over time. This is desirable as the multilayer clustering allows focusing on structural determinants, thus providing a new perspective on the analysis of trade networks and on countries' positions in the changing clusters over time.

The identification of the clusters is the first result of our analysis. A summary of the number of clusters and changes occurring over time is presented in Fig. 3 with alluvial diagrams[11], in Fig. 4 with respect to the relative importance of each cluster (as measured by their Infomap flows) and in Fig. 5 with a view to the connections among clusters.

While the overall composition of exports by SITC components and parts shows little change in the observation window (Table 1), results from the Infomap multilayer analysis show that the structure of the international trade flow underwent a very considerable change, and this is the second result of our analysis: the number of multilayer clusters decreases over the four years (from 39 in 1993 to 16 as from 2003), the main three clusters become more prevalent, and – as from 2003 - the third top cluster has only a few countries. More in detail, several of the clusters that characterize the network in 1993, subsequently merge into major clusters. This is the case of cluster 6, which in 2003 was incorporated into the cluster led by Germany, and of clusters 5, 7 and 8, which were incorporated into the cluster led by Japan[12].

The multilayer algorithm clearly yields a spatial distribution of clusters that is largely associated with the geographical position of countries, but singles out also specific sub clusters in those geographic areas, such as the ones led by the Czech Republic, Thailand, Indonesia, and Turkey, and their characterising trade: this is the third result of our analysis that would not have emerged by focusing only on networks of countries' bilateral trade by geographic area.

A fourth result refers to the consolidation, over the years, of the overall importance of the three main clusters, which remains very high (see Fig. 4 and detailed figures in Annex 6, Table A11): the Infomap flow ranges from 93%, in 1993, to 95% in 2017, although there was an increase to 96% in 2003 and a successive reduction to 93% in 2013. Clusters' relative importance and internal composition changed over time. We identify four main dynamics:

– the blue cluster, the biggest across the four years, is always led by Germany; its very high level of flow declines in 2013 but rises again in 2017;
– the grey cluster, initially the second top group, declines in importance, becoming in 2013 the third cluster. In 1993 it was led by the US and Japan, but since 2003, it has been led by the US alone and mainly embeds the NAFTA countries;
– the orange cluster, led by Japan and later on by China, becomes increasingly important, emerging, in 2013, as the second top cluster;
– two smaller clusters, one centered on Brazil and Argentina (green), and one led by the Russian Federation (brown), had a growing importance from 2003 to 2013 but declined in 2017.

Given the overarching importance of the first three clusters with respect to all the others, we will focus our analysis on these clusters and their evolution over time. Minor clusters will be discussed solely in relation to their evolving connections with the main clusters.

5.2. Internal vs external flows and overlapping nodes across clusters

The four graphs in Fig. 5 summarise the relative importance of trade of automotive components and parts within and between clusters[13]. The clusters are drawn as circles with the same colours they have in the alluvial diagram (for the nine main clusters, light green for all the others) and area proportional to the Infomap flow generated within the cluster. The thickness of links between clusters is proportional to the flow between clusters. This figure supports our fifth relevant result: cross-cluster connections increase for most clusters[14] and the overall Infomap flow generated by those connections increases from 18.5%, in 1993, to about 30%, in 2017[15] (Table 2).

For each year, we can assess the overall contribution of each country in determining meso-scale entities and their connections. Comparing 1993 with 2017, the top ten countries accounted respectively for 74% and 62% of the total Infomap flow[16], with a significant growth of several other minor countries. Connections across clusters highlight bridges across specific trades in components and parts that keep the whole

[11] An alluvial diagram represents changes in network structure over time.

[12] In 1993, these clusters were led, respectively by: JPN (cl-5) with a main trade on Reciprocating internal combustion piston engines for propelling vehicles; CZE (cl-6) with a main trade on Drive-axles with differential, whether or not provided with other transmissions; KOR (cl-7 with a main trade on Inner tubes; CHN (cl-8) with a main trade on Anchors, grapnels and parts thereof, of iron or steel.

[13] Clusters and their relations are represented in the graphs realized with the visualisation tool of Infomap Network Navigator and with Adobe Illustrator to change colours of nodes.

[14] Details in Annex 6.

[15] In order to explore Infomap flow generated within and between clusters, it is necessary to consider all states-nodes, regardless of the module they belong to and then aggregate data by module. See Annex 5 for details on the Infomap output file used to implement this analysis.

[16] Detailed figures on Infomap flow - generated within and between clusters - by country are available in Fig. A7.

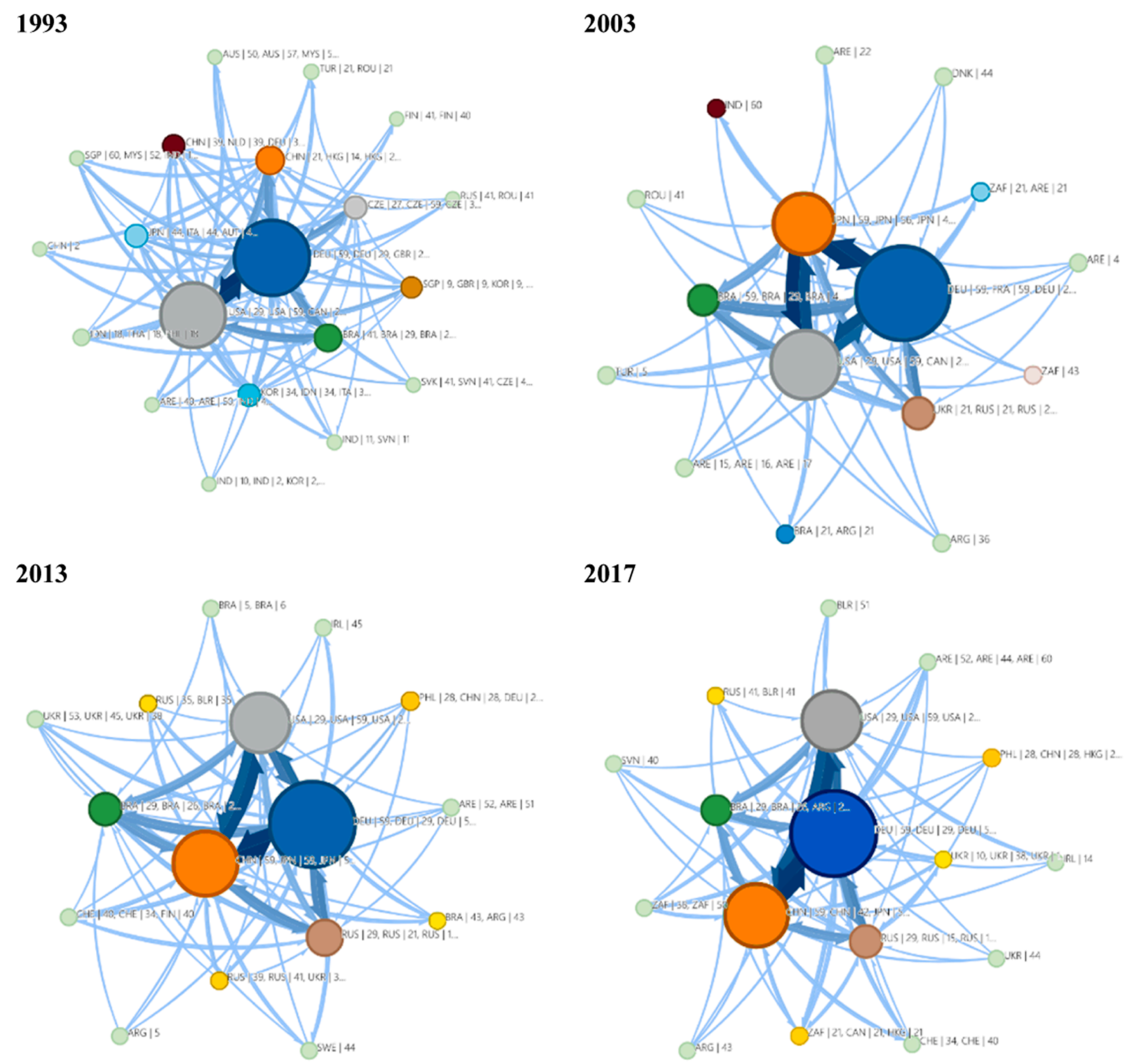

Fig. 5. Infomap flows within and between clusters.
Clusters are drawn as circles with the same colours they have in the alluvial (for the nine main clusters, light green for all the others); circles are proportional to the Infomap flow generated within the cluster; thickness of links between clusters is proportional to the Infomap flow between clusters.

Table 2
Percentage of Infomap flow generated within and between clusters, by year.

year	within the cluster	between clusters
1993	81.5%	18.5%
2003	75.5%	24.5%
2013	70.5%	29.5%
2017	70.1%	29.9%

network together. Significantly, those bridges can propagate shocks within and across clusters (depending on the nature of the shocks, e.g., a new trade agreement, a change in final demand due to new requirements for vehicles, supply chain disruptions).

Some countries are present in multiple clusters, owing to their possible role as bridges in the world automotive components trade. It is thus interesting to explore their specific characteristics: Do they show preferred countries in the direction of their trade? Are they balanced in trade with the different clusters to which they belong, or are they actually receiving most of their flow from a single cluster and from specific trade? To address these questions, in Section 6, we turn analysis from the Infomap flow to the trade shares. Having identified clusters and their determinants we can process the results of the Infomap flows within and between clusters (i.e., list of pairs state-nodes-from and -to) to produce results in terms of export and import shares, which we can

Table 3
Export shares in the top three clusters, generated within the clusters and with other clusters, by year
The first cluster is always Germany-led; the second cluster is US&Japan-led in 1993, US-led in 2003; and China&Japan-led in 2013 and 2017: the third cluster is China-led in 1993, China&Japan-led in 2003, US-led in 2003 and 2013. In the table, different colours highlight this information.

Cluster	1993			2003			2013			2017		
	within the cluster	with other clusters	Total	within the cluster	with other clusters	Total	within the cluster	with other clusters	Total	within the cluster	with other clusters	Total
1	40.6	7.0	47.6	45.3	7.8	53.1	38.1	12.0	50.1	39.0	10.8	49.9
2	41.1	7.7	48.8	23.1	3.1	26.2	11.2	17.8	29.0	10.3	17.7	28.0
3	1.0	0.4	1.5	6.5	12.6	19.1	16.3	2.8	19.1	17.3	3.5	20.8
1+2+3	82.7	15.1	97.9	74.9	23.5	98.4	65.6	32.6	98.2	66.6	32.0	98.7

Table 4
Export shares from the top three clusters, generated within the clusters and with other clusters, by year and by group of components and parts.
Colours of figures, by cluster and year, as in Table 3.

		Rubber and Metal Parts				Electrical and Electric Parts				Engines and Parts				Miscellaneous Parts			
		1993	2003	2013	2017	1993	2003	2013	2017	1993	2003	2013	2017	1993	2003	2013	2017
Within the cluster	1	4.8	3.7	3.8	3.3	1.9	1.7	1.4	1.5	7.3	8.5	7.3	7.1	26.5	31.4	25.6	27.2
	2	2.5	1.2	1.0	0.7	3.7	1.2	1.9	1.8	7.6	4.7	1.5	1.4	27.3	15.9	6.8	6.3
	3	0.0	0.5	0.9	0.8	0.0	1.7	0.7	0.8	0.3	0.8	3.6	3.9	0.7	3.6	11.1	11.8
	Total	*7.4*	*5.3*	*5.7*	*4.8*	*5.6*	*4.6*	*4.0*	*4.1*	*15.3*	*14.0*	*12.4*	*12.4*	*54.5*	*50.9*	*43.6*	*45.3*
with other clusters	1	0.7	0.5	0.9	0.8	0.2	0.2	0.3	0.4	1.3	1.6	2.7	2.4	4.8	5.5	8.1	7.3
	2	0.9	0.2	3.0	2.5	1.4	0.2	2.2	2.4	1.5	0.8	2.5	2.6	3.9	1.9	10.1	10.2
	3	0.0	1.5	0.3	0.2	0.0	2.3	0.2	0.3	0.4	2.1	0.5	0.6	0.0	6.7	1.8	2.4
	Total	*1.6*	*2.3*	*4.2*	*3.4*	*1.7*	*2.7*	*2.7*	*3.1*	*3.2*	*4.4*	*5.7*	*5.5*	*8.7*	*14.1*	*20.0*	*19.9*
1+2+3		*9.0*	*7.6*	*9.9*	*8.3*	*7.2*	*7.3*	*6.7*	*7.2*	*18.4*	*18.4*	*18.1*	*18.0*	*63.2*	*65.1*	*63.5*	*65.2*

associate with the various clusters[17].

6. From Infomap flow to trade shares: patterns of trade by cluster

In this section, we explore the patterns of export and import shares of the three main clusters, paying special attention to the embedding of satellite clusters of countries and their changing importance (Section 6.1). We then focus (Section 6.2) on trade in components and parts of internal combustion engines (ICEs), around which many changes will occur in the ongoing shift toward electric vehicles: the relative importance of countries in the various clusters can provide an indication of the impact of the reduction of trade on ICEs and their components and parts, even though other elements should be taken into account to discuss the timing and pattern of change across countries (see Pavlínek, 2022, and Schwabe, 2020a, for a broad account on this issue).

To make figures comparable across clusters, countries, components and parts, the shares of trade refer to the total of each year.

6.1. Patterns of trade shares of the three main clusters: within cluster and with other clusters

For the top three clusters, Table 3 shows the trade shares by cluster, within and between clusters, by year[18]. The overall importance of the three top clusters increases, thus confirming a result of increasing concentration of trade flows discussed in the literature. But we observe that also the cross-cluster connections generated by these clusters increases as well (from 15.1% in 1993 to 32.0% in 2017, at aggregate level), with different patterns of change by cluster.

Cluster 1 - the Germany-led cluster - increased its importance from 47.6% to 49.9% of world exports between 1993 and 2017. Over this period, it slightly increased its cross-cluster connections (from 7.0% to 10.8% of world exports) and changed its internal structure, absorbing in 2003 a minor cluster in trade of specific components, led by the Czech Republic (as observed in Section 5.1), which, in 1993, was structured around trade with countries also outside the Germany-led cluster.

In 2003, the Pacific area – which in 1993 was embedded in cluster 2 – appears to be split into two distinct trade areas, the Asian and the American, which initially reduced their overall importance on world trade (from 50.3% in 1993 to 45.3% in 2003) and then increased to 48.8% in 2017. Focusing on the US-led cluster (cl-2 in 2003), we observe that it contributes little to cross-cluster connections and, also in 2013 and 2017 (when it becomes the third cluster), its contribution is very low, being respectively 2.8% and 3.5%. In contrast, the China&Japan-led cluster (which becomes the second cluster from 2013) contributes progressively, with a larger increasing shares to cross-cluster connections: from 12.6% in 2003, to 17.8% in 2013 and 17.7% in 2017.

Cross-cluster connections can be seen also with respect to the group of components (Table 4). As can be guessed by the previous comment, the largest contribution comes from the China&Japan-led cluster that fosters cross cluster connection for all the groups of products, and significantly for the Miscellaneous Parts (which accounts for almost 20% of the cross cluster connections in 2017, half due to the China&Japan-led cluster), but also for Rubber and Metal parts, and Electrical and Electric Parts. The Germany-led cluster is second in importance in fostering cross cluster connections, with a significant contribution for the Engine and parts.

These results on cross-cluster connections represent an original contribution to the debate on trade networks in the automotive sector, allowing the assessment of which countries and which specific components and parts determine the pattern of increasing cross-cluster connections, which is discussed below.

[17] It should be noted that the Infomap multilayer algorithm does not simply measure the inflow and outflow of countries' trade, and does not reflect the weight of aggregated bilateral flows between countries. At a country level, a measure summarising those flows can be obtained by computing a centrality measure that takes into account recursive interactions among nodes.

[18] Figures for the top six clusters can be browsed in Annex 7 and can be explored online (see url in footnote 2 above).

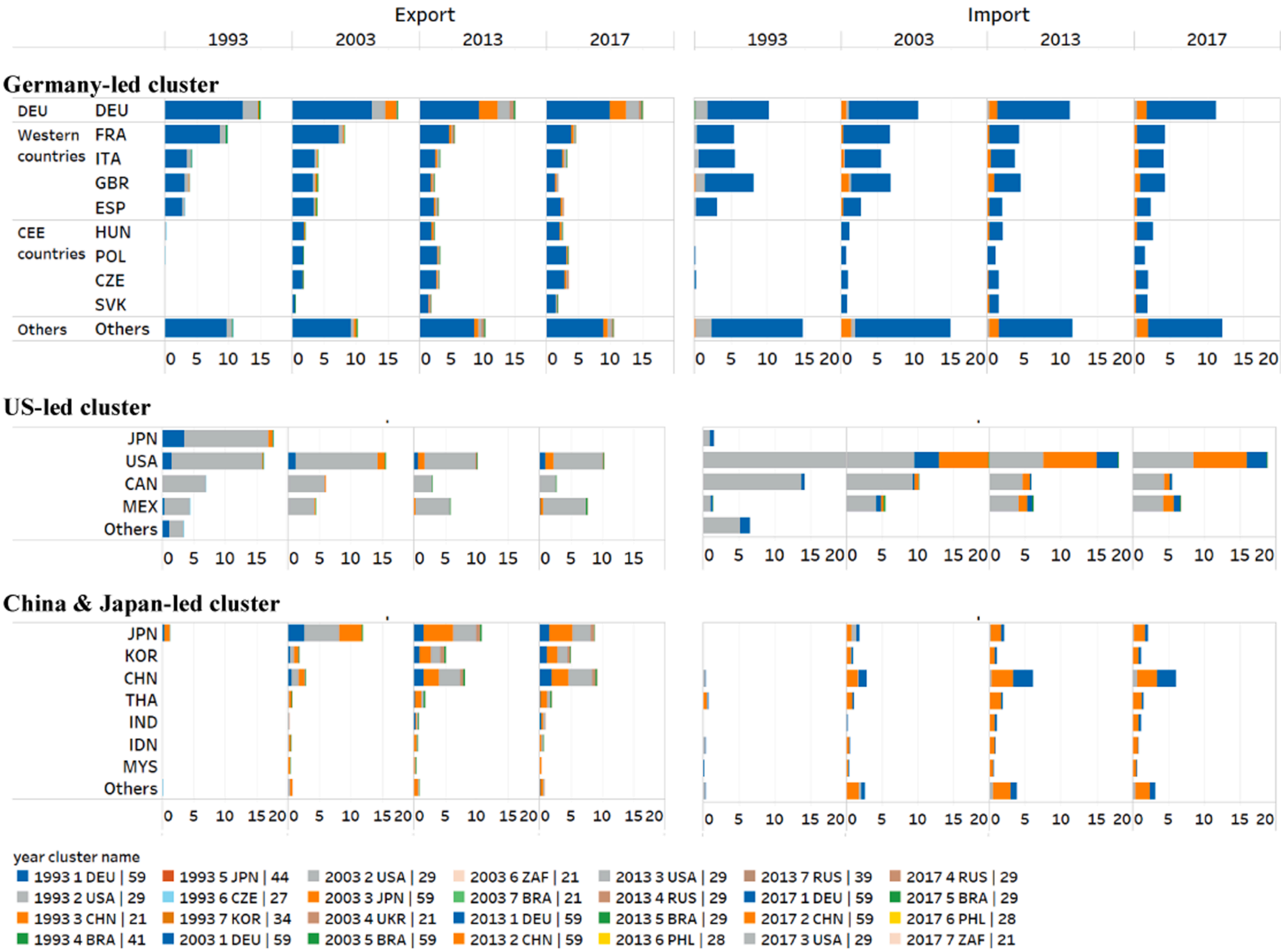

Fig. 6. Top three clusters: countries' export and import shares, by year, and cluster.

6.1.1. *Roles of countries in cross-cluster connections*

We have observed (Fig. 2) the intensification of bilateral trade flows that, over time, embedded more and more countries. Having clustered subnetworks of trade flows, we can now identify which countries contribute more and across which clusters they are active. From Fig. 6 we can easily compare the cross-cluster contribution of the main countries in each cluster over the years under analysis (countries are listed in decreasing order of their export shares within each cluster). The overall composition of the top three clusters is very different due to the heterogeneity in the number of countries involved in each cluster, in their relative importance, and in their cross-cluster contribution. Due to these differences it is expedient to comment separately the three main clusters.

6.1.1.1. The Germany-led cluster. The composition of countries of the Germany-led cluster shows the practically stable share of Germany's exports, the declining importance of the four countries structuring this cluster in 1993 (France, Italy, Spain, and the United Kingdom), that were supplanted by the CEE countries (Czech Republic, Hungary, Slovakia and Poland). The former reduced their overall share from 21.3% in 1993 to 12.7% in 2017, while, over the same period, the latter passed from 0.5% of world exports in 1993 to 11.4% in 2017 (see Table A16). The 21 other countries in this cluster account for a fairly stable overall share of world exports (about 10.4%), while they started with a larger (14.1% in 1993) and initially increasing share of imports that then fell to 12.7% in 2017. Most of these countries are other European countries embedded in the cluster, with a smaller proportion of countries also present in the US-led and the China&Japan-led clusters.

With respect to cross-cluster connections, the greater contribution to exports is given by Germany, while the four main Western countries of the cluster give a lower and decreasing contribution (from 3.1% in 1993 to 2.4% in 2017, with slight differences among the four countries), which is not completely compensated by the CEE countries (rising from 0.5% in 2003 to 1.6% in 2017). The cross-cluster connections made possible by imports of components and parts from countries outside the clusters (7.5% in 2017) are smaller than the ones for exports, returning in 2017 to the same level as 1993, after a 1.2% reduction in 2003 and a slight increase in 2013.

Examining export and import shares, it emerges that Germany increased its export share towards both the US-led and the China &Japan-led clusters, and to a lesser degree towards the other minor clusters (led, respectively, by Brazil, Ukraine and Russia). Germany's imports from other clusters were less relevant, and were concentrated specifically from the China&Japan-led cluster since 2003. In this respect, similar dynamics can be observed also for the other countries in this cluster.

6.1.1.2. The US-led cluster. In 1993, Japan was part of the US-led cluster, with shares of world exports of 17.7% for Japan and 16.2% for the US, and the other two main countries - Canada and Mexico -

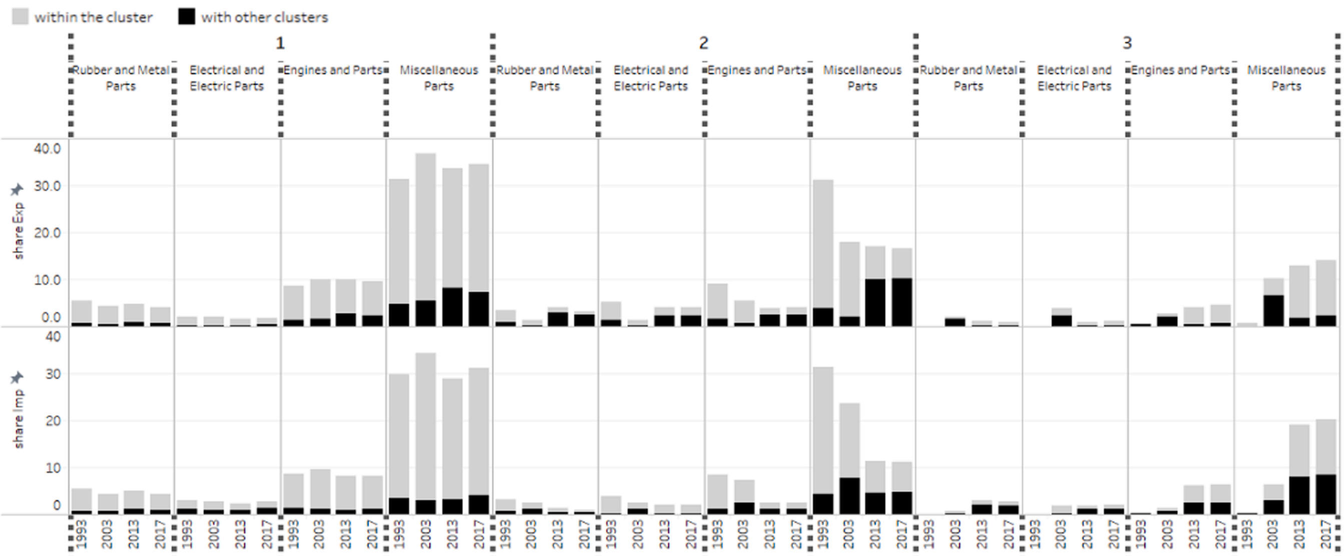

Fig. 7. Share of export and imports of group of components and parts, by cluster and year, within the cluster and with other cluster.

Table 5
Contribution of the top 10 components and parts to cross-cluster connections: export shares by cluster and year. Components and parts are ranked according to their total export shares, in 1993.

SITC codes	SITC code description	Group of SITC codes	with other clusters											
			1				2				3			
			1993	2003	2013	2017	1993	2003	2013	2017	1993	2003	2013	2017
78439	Other parts and accessories of the motor vehicles of groups 722, 781, 782 and 783	Miscellaneous Parts	2.7	2.5	3.0	2.9	2.0	0.9	4.6	5.1		3.1	0.8	0.9
78434	Gearboxes of the motor vehicles of groups 722, 781, 782 and 783	Miscellaneous Parts	0.7	0.9	1.8	1.5	0.9	0.3	2.0	1.8	0.0	1.6	0.4	0.6
78432	Other parts and accessories of bodies (including cabs), of the motor vehicles	Miscellaneous Parts	0.5	1.1	1.5	1.4	0.4	0.5	1.4	1.4		0.9	0.2	0.3
6251	Tyres, pneumatic, new, of a kind used on motor cars (including station wagons and racing cars)	Rubber and Metal Parts	0.5	0.3	0.6	0.5	0.7	0.1	2.0	1.6		1.0	0.1	0.1
77812	Electric accumulators (storage batteries)	Electrical and Electric Parts	0.2	0.2	0.2	0.3	0.6	0.1	1.4	1.9		1.2	0.2	0.3
78433	Brakes and servo-brakes and parts thereof, of the motor vehicles of groups 722, 781, 782 and 783	Miscellaneous Parts	0.4	0.5	0.5	0.5	0.2	0.1	1.0	1.0		0.6	0.1	0.1
77831	Electrical ignition or starting equipment of a kind used for spark-ignition or compression-ignition ICE	Engines and Parts	0.2	0.2	0.2	0.2	0.3	0.1	0.8	0.8		0.6	0.2	0.2
71323	Compression-ignition internal combustion piston engines (diesel or semi-diesel)	Engines and Parts	0.2	0.3	0.8	0.8	0.1	0.1	0.3	0.3	0.4	0.2	0.1	0.1
78435	Drive-axles with differential, whether or not provided with other transmission components	Miscellaneous Parts	0.1	0.1	0.4	0.4	0.1	0.0	0.7	0.6	0.0	0.3	0.1	0.1
77834	Electrical lighting or signalling equipment (excluding articles of subgroup 778.2)	Engines and Parts	0.1	0.1	0.4	0.4	0.1	0.1	0.5	0.6		0.2	0.1	0.1

accounting, respectively, for about 7.0% and 4.4%. The remaining 16 countries in the cluster accounted an overall 3.5% of exports.

After 1992, the NAFTA attracted significant foreign direct investments from Japan to the US, Mexico and Canada (Carreto Sanginés et al., 2021). Since 2003, the cluster is led by the US and embeds the three countries belonging to NAFTA, with Canada and Mexico trading mainly within the cluster, for both exports (respectively 2.6% and 6.9%) and imports (4.4% and 4.3%). While US exports declined continuously, (from 15.6% in 2003 to 10.2% in 2013 and 10.4% in 2017), Mexico's importance increased over time (to 7.7% in 2017) at the expense of Canada (whose share falls to 2.7% in 2017) (see Figs. 2 and 6; and for more details Tables A18 and A19). As for imports, in 2003 US trade across clusters accounts for 10.5% of the world's total, while 8.6% were imports within the cluster. Similar shares were observed in 2013.

6.1.1.3. The China&Japan-led cluster. The China&Japan-led cluster has emerged since 2003, with a growing importance - over the years - of China and South Korea, and – to a lesser extent - Thailand, India,

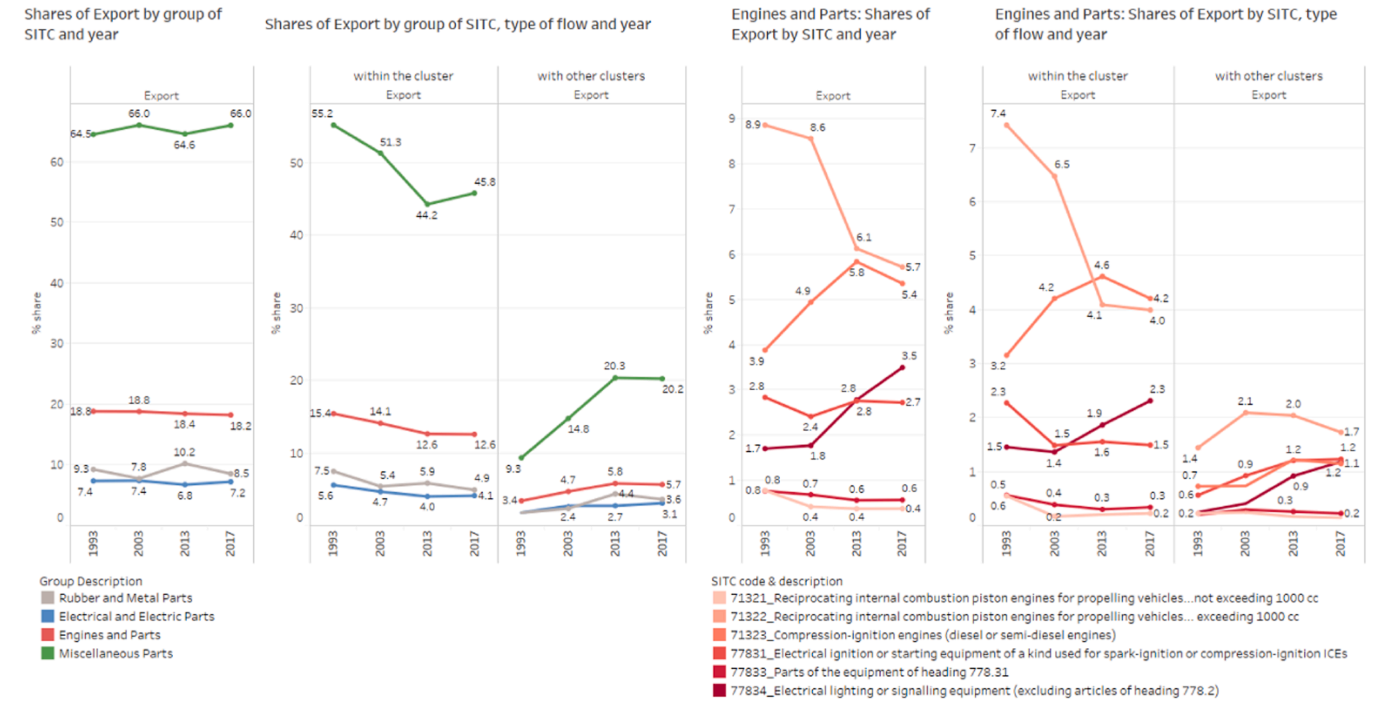

Fig. 8. Export trade shares (total, within and between clusters), by group of automotive components and parts, and by SITC code of Engine and Parts, 1993, 2003, 2013, 2017.

Table 6
ICEs: Trade shares of export from the top six countries, by country, within the top three clusters and with other clusters, 2017.
SITC codes: 713.21, 713.22, 713.23, 778.31, 778.33 and 778.34. Countries are ranked by total share in the year.

	Total	within the cluster				with other clusters			
Country.From		*Total*	1	2	3	*Total*	1	2	3
USA	2.41	*1.99*			1.99	*0.42*			0.42
DEU	2.18	*1.35*	1.35			*0.83*	0.83		
JPN	1.69	*0.64*		0.64		*1.05*		1.05	
MEX	1.65	*1.49*			1.49	*0.16*			0.16
HUN	1.14	*0.96*	0.96			*0.18*	0.18		
CHN	1.14	*0.31*		0.31		*0.83*		0.83	
6 countries	10.21	*6.72*	2.30	0.95	3.47	*3.49*	1.02	1.89	0.58
All countries	18.23	*12.57*	7.08	1.44	3.94	*5.66*	2.36	2.58	0.60

Indonesia and Malesia. Six other countries are embedded in this cluster for some trade, mainly for imports. The overall pattern of trade with other clusters is specular with the above observations on the Germany-led and the US-led clusters. The largest impact to the upsurge of this cluster is given by China, exploiting the advantage of having become a member of WTO in 2001 and having cumulated strong production relations with OEMs and global tiers-1, through the Chinese joint venture policy that attracted them and created strong production links both in the European markets and North-American market.

With respect to exports, the US is very important for China; Brazil and Argentina are important partners for Korea, Thailand and Indonesia, while Russia is a very important partner for several countries in the cluster. The other countries embedded in this cluster - Thailand, Hong Kong, India, Indonesia and Malaysia - have different patterns of trade shares and, since 2003 they moved towards more balanced trade shares with the US-led and the Germany-led clusters.

6.1.2. Roles of components and parts in cross-cluster connections

Over the 25 years considered in this study, the three main clusters show different dynamics with respect to the group of components and parts (Fig. 7). Indeed, while cluster 1 has a relatively stable composition of exports and imports in terms of shares (both within and with other clusters), clusters 2 and 3 have opposite trends in Miscellaneous Parts.

Table 5 shows, for the three main clusters, the top 10 items that contribute to cross-cluster connections with a share of over 0.1% of world trade. "*Other parts and accessories of the motor vehicles…*" - itself a miscellaneous group – in 2017 contributed with 8.9% to all exports across clusters (it was 4.9% in 1992), with the China&Japan-led cluster accounting for 5.1%. The China&Japan-led and the Germany-led clusters contribute to cross-cluster connections through exports of "*Gearboxes of the motor vehicles…*" with a similar export share (respectively, 1.8% and 1.5%) and "*Other parts and accessories of bodies (including cabs), of the motor vehicles*" (with a share of 1.4%). The fourth item is "*Tyres, pneumatic, new, of a kind used on motor cars (including station wagon)*" for which the China&Japan-led cluster is three times more important than the German-led one (respectively, 1.6% and 0.5% of exports). The next five items[19] show a larger importance of the China&Japan-led cluster. Finally, in the case of "*Compression-ignition internal combustion piston engines (diesel or semi-diesel)*" the Germany-led cluster - and most notably Germany itself - was activating the higher cross-cluster connection in 2013.

Beyond the above comments on biggest single items, the web of interconnections involves many countries and components and parts. Detailed patterns of groups of products can be explored in the Supplementary Material (Annex 8) and navigated with the online tool.

6.2. From vehicles with internal combustion engines (ICE) to electric vehicles

It is estimated that, with the transition from the internal combustion engine (ICE) to the electric engine, the average number of powertrain components could drop from 1500 to just 230 (Schulte, 2020). In this section, we use the results of the analysis reported so far to gauge the potential effects of the electrical transition on trade, that is, which countries and which bilateral trade flows could be more negatively affected, though we cannot say yet which new trade flows, competences and countries will emerge. To this end, we focus our attention on the components required to convert the engine's power into actual movement namely, the engine, transmission, driveshaft, differentials, axles. In other terms, we focus on the components that connect the engine to the wheels, which are represented by the six SITC codes in the group Engines and Parts[20]. Their share in the total exports of the four groups of automotive components and parts is relatively stable over the years. However, though still accounting for the largest part of total trade, their share of within-cluster trade declines (from 15.4%, in 1993, to 12.6% in 2017) (Fig. 8). Moreover, the dynamics of the sub-groups within Engines and Parts varies considerably, reflecting the changes in location and product that the automotive sector underwent over the period.

The overall impact on trade of the transition from ICE to electric will affect the leading countries: in 2017, 56% of the total export of Engines and Parts is generated by six countries: United States, Germany, Japan, Mexico, Hungary, China (see Table 6 and details in Annex 10). Though the largest part occurs within clusters, almost one third of those exports go to countries in other clusters (a feature in line with what we observed above about cross-cluster connections)[21]. This means that the transition risks disrupting a large part of transactions within each cluster, especially the ones headed by the US and Germany.

On the import side, in 2017 the US was the largest importer of Engines and Parts from countries in other clusters (1.7%), and it imported a similar share from within its cluster. Conversely, Germany imported more from countries within the cluster than from countries in other clusters. Finally, in line with the strategy of its car makers, Japan imported small shares from other countries, mainly from the Germany-led cluster.

These preliminary results suggest that the transition could entail a significant restructuring of trade flows, especially within clusters, which could affect more heavily the integrated peripheries, while also impacting the leading countries in their trade between clusters[22].

7. Discussion and conclusion

The automotive industry is undergoing a radical transformation. The transition to electric and digital vehicles, as well as environmental and geopolitical challenges, are bound to change the global structure of automotive production. The pandemic first, and then Russia's war with Ukraine and the ensuing Western sanctions have disrupted nearly every aspect of the global supply chains, as the lack of even a single component may be enough to halt production. Actual or anticipated shortages have led to reconsidering the need to shorten value chains, diversify supplies and/or identify those components that need to be re-shored to prevent dependence on overseas sources for critical parts. Moreover, with the new world of mobility and electrification accelerated by climate change, a whole segment of the value chain producing parts and components for the internal combustion engine will have to restructure or downsize. Batteries and chips, and their inputs, are at the forefront in the OEMs' worries.

Although the geography of countries bilateral trades is only one of the many dimensions impacting on the configuration of the automotive industry, in the complex set of interacting changes, occurring at company level, country policy level and in the geopolitical environment, the definition of the geography of trade can provide a benchmark for the analysis of the possible repercussions of the ongoing transformations in the various specialisations of many regions and countries involved in the automotive GVC.

The analytical model implemented to define the geography of trade before all the now occurring changes is not meant as a deterministic framework or as a prediction tool. Too many technical developments, product innovations (such as *mobility as a service* that is expected to impact the number of cars to be produced), geopolitical processes, renewable energy production and energy cost impact on the future configuration of the automotive GVC, making it essentially unpredictable through trade network analysis. With regard to such a complex scenario, future analyses of the outcome of those many interacting elements will benefit from a pre-post comparison of networks configurations outlined using the presented analytical framework.

Our analytical model allows to conceptualise the notions of "regionalisation" and "globalisation" as emergent properties of the clusters of countries and trades identified in the world trade network, and not as *a priori* attributions of countries in their geographical position. We show that, while the relative importance of the main clusters and of some individual countries changes significantly, connections between clusters increase over time, providing in this way an original contribution to the debate on regionalisation vs. globalisation on GVCs. This twin dynamic characterizes the automotive international trade networks over the 25 years under analysis.

With automotive global value chains in the described state of turmoil, the definition of the pre-turmoil situation presented in the paper can prove an indispensable starting point for analysis of the possible repercussions of the current technological and geo-political transition on geographical clusters and the sectorial specialisations of the main regions and countries. In the economic literature on international trade, study of the automotive global value chains has been addressed using network analysis, focusing on the geographical regions and on the different types of bridging role of countries, while largely overlooking the contribution of countries' bilateral trade in components and parts to the structuring of the subnetwork of countries and their specific position in the overall trade network.

Many dimensions impact on international trade network (recalled at the end of Section 2): skills, wages, regulations, innovation ecosystems and absorptive capacity shape the structure of supply of automotive components and parts, which also depends on other production specialisations in the country, the location of domestic and foreign car makers' plants in the country, the role assigned by carmakers to supply from that country with respect to their global supply chains. Countries' centrality in international trade depends on those dimensions. In

[19] Namely: *"Electric accumulators (storage batteries)", "Brakes and servo-brakes and parts thereof, of the motor vehicles of group", "Electrical ignition or starting equipment of a kind used for spark-ignition", "Drive-axles with differential, whether or not provided with other transmission"* and "*Electrical lighting or signalling equipment"*.

[20] The list of items classified in the SITC codes 713.21, 713.22 and 713.23 is available in Annex 8.

[21] Explore on line data on internal combustion engines: shares of export and import by country, SITC code and year [flows within and between clusters (part B)].

[22] For a mapping in the emerging electro mobility, see Russo et al. (2022) and Acerbi et al. (2022) on battery production.

addition to these dimensions one must consider that trade network is only one of the various interrelated networks that should be considered for a full understanding of the trade pattern: networks of technologies, competences and organisations, regional trade agreements and preferential trade arrangements are intertwined with the trade flows operated by TNCs (car manufacturers and Tier 1 suppliers), which in turn affect countries' trading. Analysis of those networks will call for ad hoc investigation into the dynamics of change which occurred in the automotive value chains, with a specific focus on who produces what and where.

With a focus on bilateral trade networks, the paper provides original contributions on both analytical and descriptive perspective.

The analytical value that is added by the multilayer clustering method presented in the paper lies in the identification of clusters and in the adoption of a metrics that allows to compare over time the changes in trade flows which led to the changing configuration of clusters. The analysis has evidenced answers to the three empirical issues, presented in the Introduction: an increasing concentration of trade; the emerging spatial distribution of clusters, confirming the relevance of proximity in trade exchanges and the presence of sub clusters in those geographic areas, that would not have emerged by focusing only on networks of countries' bilateral trade by geographic area; and the increase of cross-cluster connections, thus highlighting increasing cross-region integration.

We chose to focus on the three main clusters – the Germany-led cluster, the US-led cluster and the China&Japan-led cluster - to highlight important examples of persisting differences in within-cluster relations. As for the changes in the geography of trade relations, we find denser and more hierarchical clusters generated, respectively, by Germany's trade relations with EU countries, the US preferential trade agreements with Canada and Mexico, and the surge of China. The results reflect the impact of the signing and undoing of trade treaties in changing geopolitical scenarios. The major shift in international trade driven by NAFTA (in particular the triangulation of trades occurring via Mexico) can be compared with the effects expected under the new USMCA trade agreement, and the repositioning of the main OEMs following the new protectionist policies inaugurated by the Trump administration and continued by the current one.

Conversely, the structural changes within the Germany-led cluster highlight the strategy of the German OEMs aimed at integrating the CEE countries in ever closer connections, each of them still maintaining trade relations outside the Germany-led cluster, thus strengthening their connections with (but also their dependence on) world trade.

Focusing on the composition of trade, the largest clusters show a similar structure, although the quality and characteristics of the various components and parts are likely to differ significantly. The Infomap multilayer analysis allows to single out which components and parts determined the relative positions of countries in the various clusters; it also identifies smaller clusters that turn out to be highly specialised with a different trade orientation. Finally, the detailed analysis focusing on individual components and parts casts light on the trade patterns related to the production of internal combustion engines (ICEs). The results show the different dynamics of parts and components for ICEs over time, and the potential impact of the transition to electric vehicles on the main countries exporting ICEs. Although new components will be needed for electric vehicles, their production will not necessarily be located in the same places where ICEs and their components are now being produced (Pavlínek, 2022). Analysis of the potential impact of these changes will call for more detailed classification of trade statistics and information on the production structure of the countries at present involved in the export of ICE components and parts, and of those countries that will be specialising in components and parts for electric mobility.

To conclude, over the years, the regionalisation of trade thickened (many small clusters of countries disappear), but the links between clusters almost doubled at the aggregate level, with a significant contribution of the countries in the China&Japan-led cluster.

The application of the multilayer method to the automotive international trade networks evidenced an emerging model characterised by regionalization – with denser and more hierarchical large clusters complemented by smaller specialized ones - and cross-region integration: this is the most original analytical result of the paper. This twin dynamic of regionalization and cross-region integration is likely to be very different in the coming years, with the reorganization of global value chains following the pandemic, the war and the transition to electric and autonomous driven vehicles in Europe, US and China.

The issue of redesigning the supply chain has entered the agenda of carmakers and debates on national/local sovereignty, together with the need to reconsider redundancy as a more efficient solution - compared to just-in-time or free-pass production methods - and logistics and transport as possible causes of bottlenecks in supply chains. In the short term, the impact of these events has been shifted on to price increases along the supply chain or has affected cars' performance (as in the case of cars delivered in reasonable time and with a reasonable price, but with fewer microchip devices). In the medium term, reorganisation of the automotive industry will be marked by the carmakers' commitment to comply with the requirements of CO_2 emissions, durability of batteries, smarter mobility – issues subject to heated debate and on which there is no agreement between the countries (as emerged in COP26 and COP27). Our analysis, presenting a picture of the trade conditions *before* these changes, offers a benchmark for analysis of the changes *post*-transition.

CRediT authorship contribution statement

Margherita Russo: Conceptualization, Data curation, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Fabrizio Alboni:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jorge Carreto Sanginés:** Funding acquisition, Writing – review & editing. **Manlio De Domenico:** Formal analysis, Investigation, Methodology. **Giuseppe Mangioni:** Formal analysis, Investigation, Methodology, Software, Writing – review & editing. **Simone Righi:** Formal analysis, Investigation, Methodology, Software, Writing – original draft. **Annamaria Simonazzi:** Conceptualization, Funding acquisition, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

Acknowledgments

The paper is part of the research project "Geopolitical and technological challenges for the automotive global value chains", PI Annamaria Simonazzi, funded by INET. The application on Mexico has been developed under the complementary project "Digital transformation in the automotive supply chain in Mexico", PI Jorge Carreto Sanginés, funded by UNAM PAPIIT IN309620. A preliminary version of the paper has been published in the INET WP Series. The authors wish to thank INET for the permission to use the results of that analysis for the present version.

The authors wish to thank Emmanuel Lazega, Pietro Panzarasca and Riccardo Righi for their comments on the presentation of preliminary results of this paper at the ARS'19 Seventh International Workshop, and comments and suggestions emerging in the discussion with participants at the c.MET05 Policy Research Meeting on 31st March 2021, Italy, at the Gerpisa 2021 Colloquium, at the Conference on "L'industria dell'auto e gli investimenti della Cina nell'era dell'auto elettrica e della mobilità sostenibile", Modena University, 2021, and at the EUSN 2021 Conference. A special thanks to Martin Rosvall, who highlighted which output files could be used in the analysis of Infomap flow between clusters, and to Emanuele Murgolo for copy editing.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.strueco.2023.07.006.

References

Acerbi, B., Alboni, F., Kern, J., Russo, M., 2022. What can we see at the dog and pony show? Understanding actors in the EV market based on exhibitor patterns at the largest battery trade shows. Presentation at. In: Proceedings of the Gerpisa 2022 Colloquium.
Amighini, A., Gorgoni, S., 2014. The international reorganisation of auto production. World Econ. 37 (7), 923–952. https://doi.org/10.1111/twec.12091.
Arenas, A., De Domenico, M., 2016. Nonlinear dynamics on interconnected networks. Phys. D Nonlinear Phenom. 323–324, 1–4. https://doi.org/10.1016/j.physd.2016.03.016.
Barigozzi, M., Fagiolo, G., Mangioni, G., 2011. Identifying the community structure of the international-trade multi-network. Phys. A Stat. Mech. Appl. 390 (11), 2051–2066. https://doi.org/10.1016/j.physa.2011.02.004.
Blondel, V.D., Guillaume, J.L., Lambiotte, R., Lefebvre, E., 2008. Fast unfolding of communities in large networks. J. Stat. Mech. Theory Exp. (10), P10008, 2008. http://stacks.iop.org/1742-5468/2008/i=10/a=P10008.
Boccaletti, S., Bianconi, G., Criado, R., del Genio, C.I., Gómez-Gardeñes, J., Romance, M., Sendiña-Nadal, I., Wang, Z., Zanin, M., 2014. The structure and dynamics of multilayer networks. Phys. Rep. 544 (1), 1–122. https://doi.org/10.1016/j.physrep.2014.07.001.
Brincks, C., Domański, B., Klier, T., Rubenstein, J.M., 2018. Integrated peripheral markets in the auto industries of Europe and North America. Int. J. Automot. Technol. Manag. 18 (1), 1–28.
Carreto Sanginés, J., Russo, M., & Simonazzi, A. (2021). Mexico's automotive industry: a success story? Institute for New Economic Thinking Working Paper Series, 166. 10.36687/inetwp166.
Celi, G., Ginzburg, A., Guarascio, D., Simonazzi, A., 2018. Crisis in the European Monetary Union: A Core-Periphery Perspective, 1 Edition. Routledge.
De Domenico, M., Lancichinetti, A., Arenas, A., Martin, R., 2015. Identifying modular flows on multilayer networks reveals highly overlapping organization in interconnected systems. Phys. Rev. X 5 (1). https://doi.org/10.1103/PhysRevX.5.011027.
De Domenico, M., Granell, C., Porter, M.A., Arenas, A., 2016. The physics of spreading processes in multilayer networks. Nat. Phys. 12 (10), 901–906. https://doi.org/10.1038/nphys3865.
De Domenico, M., Solé-Ribalta, A., Cozzo, E., Kivelä, M., Moreno, Y., Porter, M.A., Gómez, S., Arenas, A., 2013. Mathematical formulation of multilayer networks. Phys. Rev. X 3 (4), 041022. https://doi.org/10.1103/PhysRevX.3.041022.
Fagiolo, G., Reyes, J., Schiavo, S., 2009. The world-trade web: topological properties, dynamics, and evolution. Phys. Rev. E 79 (3), 036115. https://doi.org/10.1103/PhysRevE.79.036115.
Fortunato, S., Hric, D., 2016. Community detection in networks: a user guide. Phys. Rep. 659, 1–44. https://doi.org/10.1016/j.physrep.2016.09.002.
Freyssenet, M., Shimizu, K., Volpato, G., 2003. Conclusion: regionalization of the American and Asian automobile industry, more than globalization. In Freyssenet, M., Shimizu, K., Volpato, G., (eds.), Globalization or Regionalization of the American and Asian Car Industry? Palgrave Macmillan UK, pp. 209–230. https://doi.org/10.1057/9780230554818_9.
Girvan, M., Newman, M.E., 2002. Community structure in social and biological networks. Proc. Natl. Acad. Sci. 99 (12), 7821–7826.
Gorgoni, S., Amighini, A., Smith, M., 2018. Automotive international trade networks: a comparative analysis over the last two decades. Netw. Sci. 6 (4), 571–606. https://doi.org/10.1017/nws.2018.18.
Gould, R.V., Fernandez, R.M., 1989. Structures of mediation: a formal approach to brokerage in transaction networks. Sociol. Methodol. 19, 89. https://doi.org/10.2307/270949.
Harvey, D., 2014. Seventeen Contradictions and the End of Capitalism. Oxford University Press, USA.
Hausmann, R., Hidalgo, C.A., Bustos, S., Coscia, M., Chung, S., Jimenez, J., Simões, A., Yildirim, M.A., Harvard University. Center for International Development, John F. Kennedy School of Government, Massachusetts Institute of Technology. Media Laboratory. Macro Connections Research, & Massachusetts Institute of Technology, 2011. The Atlas of Economic Complexity: Mapping Paths to Prosperity. Center for International Development, Harvard University : Harvard Kennedy School : Macro Connections, MIT : Massachusetts Institute of Technology. http://www.hks.harvard.edu/centers/cid/publications/featured-books/atlas.
Hausmann, R., Hwang, J., Rodrik, D., 2007. What you export matters. J. Econ. Growth 12 (1), 1–25. https://doi.org/10.1007/s10887-006-9009-4.
Hidalgo, C.A., 2021. Economic complexity theory and applications. Nat. Rev. Phys. 3 (2), 92–113. https://doi.org/10.1038/s42254-020-00275-1.
Hoeft, F. (2020). Assessing organisational capabilities of incumbent car manufacturers in light of current influencing factors. Gerpisa.
Hufbauer, G.C., & Jung, E. (2021). Scoring 50 years of US industrial policy. PIIE BRIEFING 21-5, 110.
Hummels, D., 2007. Transportation costs and international trade in the second era of globalization. J. Econ. Perspect. 21 (3), 131–154. https://doi.org/10.1257/jep.21.3.131.
Kivela, M., Arenas, A., Barthelemy, M., Gleeson, J.P., Moreno, Y., Porter, M.A., 2014. Multilayer networks. J. Complex Netw. 2 (3), 203–271. https://doi.org/10.1093/comnet/cnu016.
Klier, T.H., Rubenstein, J.M., 2008. Who Really Made Your Car?: Restructuring and Geographic Change in the Auto Industry. W.E. Upjohn Institute. https://doi.org/10.17848/9781435678552.
Miller, Mc.P., Lynn, S.-L., Cook, J.M., 2001. Birds of a feather: homophily in social networks. Ann. Rev. Sociol. 27 (1), 415–444.
Pavlínek, P., 2018. Global production networks, foreign direct investment, and supplier linkages in the integrated peripheries of the automotive industry. Econ. Geogr. 94 (2), 141–165. https://doi.org/10.1080/00130095.2017.1393313.
Pavlínek, P., 2020. Restructuring and internationalization of the European automotive industry. J. Econ. Geogr. 20 (2), 321–354. https://doi.org/10.1093/jeg/lby070.
Pavlínek, P., 2022. Transition of the automotive industry towards electric vehicle production in the east European integrated periphery. Empirica. https://doi.org/10.1007/s10663-022-09554-9.
Piccardi, C., Tajoli, L., 2018. Complexity, Centralization, and Fragility in Economic Networks. Edited by Samir Suweis. PLOS ONE 13 (11), e0208265. https://doi.org/10.1371/journal.pone.0208265.
Rosvall, M., Bergstrom, C.T., 2008. Maps of random walks on complex networks reveal community structure. Proc. Natl. Acad. Sci. 105 (4), 1118–1123. https://doi.org/10.1073/pnas.0706851105.
Russo, M., Alboni, F., Bonifati, G., Carreto Sanginés, J., Pavone, P., Simonazzi, A., 2022. Agents and artefacts in the emerging electric vehicle space. Int. J. Automot. Technol. Manag. 22 (SI), 150–177.
Schwabe, J., 2020a. Risk and counter-strategies: the impact of electric mobility on German automotive suppliers. Geoforum 110, 157–167. https://doi.org/10.1016/j.geoforum.2020.02.011.
Schwabe, J., 2020b. From "obligated embeddedness" to "obligated Chineseness"? Bargaining processes and evolution of international automotive firms in China's New Energy Vehicle sector. Growth Change 51 (3), 1102–1123. https://doi.org/10.1111/grow.12393.
Simonazzi, A., Carreto Sanginés, J., & Russo, M. (2020). The future of the automotive industry: dangerous challenges or new life for a saturated market? Institute for New Economic Thinking Working Paper Series, 141. https://www.ineteconomics.org/research/research-papers/the-future-of-the-automotive-industry-dangerous-challenges-or-new-life-for-a-saturated-market.
Simonazzi, A., Carreto Sanginés, J., Russo, M., 2022. The world to come: key challenges for the automotive industry. Economia Lavoro 57 (1), 7–23. https://doi.org/10.7384/105051.
Sturgeon, T., Van Biesebroeck, J., Gereffi, G., 2008. Value chains, networks and clusters: reframing the global automotive industry. J. Econ. Geogr. 8 (3), 297–321. https://doi.org/10.1093/jeg/lbn007.
Tacchella, A., Cristelli, M., Caldarelli, G., Gabrielli, A., Pietronero, L., 2012. A new metrics for countries' fitness and products' complexity. Sci. Rep. 2 (1), 723. https://doi.org/10.1038/srep00723.
Womack, J.P., Jones, D.T., Roos, D., 1991. The Machine That Changed the World: How Japan's Secret Weapon in the Global Auto Wars Will Revolutionize Western Industry, 1st HarperPerennial ed. HarperPerennial.
Zhu, Z., Morrison, G., Puliga, M., Chessa, A., Riccaboni, M., 2018. The similarity of global value chains: a network-based measure. Netw. Sci. 6 (4), 607–632. https://doi.org/10.1017/nws.2018.8.