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Learning, technological competition and network structure in the aero-engine industry

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LEARNING, TECHNOLOGICAL COMPETITION AND NETWORK STRUCTURE IN THE AERO-ENGINE INDUSTRY♣.

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Abstract

This paper provides a novel contribution for specifying the role of demand for technological competition. The focus is on the analysis of the mechanisms of technological learning and spillovers occurring in different structures of networks of vertically-related industries. The paper offers a detailed and original empirical analysis of technological competition among suppliers and structure of the network of two vertically related-industries, namely the commercial jet and turboprop aero-engine and aircraft industries. Technological performances of actors are measured through measures of output of the technological activity.

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1. Introduction

This paper contributes to understand the relations between technical progress and vertical organisation of industries at a micro-level. This allows to propose a novel specification of the role of demand for technical progress, which is based on the analysis of the mechanisms of technological learning and spillovers occurring in different structures of networks of vertically-related industries. The role of demand has been repeatedly emphasised in the literature on technical progress (Dosi, 1982; Saviotti and Metcalfe, 1984; Lancaster, 1971; see also the special issue of the Journal of Evolutionary Economics (2001) for recent contributions). However, we believe that the micro-mechanisms of interactions between suppliers and users of innovations and their impact on technical progress have not been sufficiently specified and, moreover, have not been dealt with quantitatively.

In this paper we propose that the *structure of the network* of relations between producers and users of innovations affects the nature (speed and variety) of the learning processes of firms and technological competition among players, their technological performances and the rate of technical progress. We claim that the processes of technological *learning, spillover and competition*, which are characteristics of different levels of cohesion of the network, affects the rate of *technological competition* among actors.

The paper reviews the literature on measurement of technical progress, emphasising the relevant indicators for studying technological competition among actors based on technological output indicators. A detailed and original empirical analysis is developed to explore the hypothesis of different dynamics of technological competition in different structures of networks of vertically related-industries. The objects of the empirical analysis are the commercial jet and turboprop aero-engine and aircraft industries, respectively from 1958 to 1997 and from 1948 to 1997.

Data on technical parameters on the supply side have been used to obtain a segmentation of the market into three product classes in the jet and two product classes in the turboprop. Segmentation has been defined through cluster analysis, and has been supported by qualitative information drawn from specialised press, interviews with technical experts, company reports and publications on the history and structure of the aviation industry. Within each cluster technometric indicators (Grupp, 1998) have been computed to identify the technological trajectories at the industry level and the position of firms along the technological frontier.

The empirical analysis support the hypothesis of a more intense technological competition in the core of hierarchical networks. Competition is characterised by the absence of a single technological leader and by the substitutions of leaders over time, which is more rapid in cohesive sub-groups. On the contrary in partitioned networks, technological competition is weaker and different companies can survive in the market and occupy important positions in terms of market shares, while following parallel technological trajectories.

2. Vertical structure of the market and technical progress

This work draws from contributions on technical progress and technological trajectories, learning and interaction among heterogeneous agents (Dosi, 1982, 1988; Chiaromonte and Dosi, 1993; Cohendet, 1993; Lundvall, 1993; Llerena and Oltra, 2000), and further extends the idea that the emergence and the evolution of technological trajectories depends on learning processes among suppliers and users.

The paper also proposes to analyse quantitatively the micro-mechanisms of interactions between suppliers and users and the technological competition among suppliers by focusing on direct measures of output of the technological activity. This allows to avoid limitations of input indicators such as R&D investments, or intermediate input such as patents, which have been the basis of many theoretical game-based models of technological competition (for a survey see Reinganum, 1989).

As it has been argued by Dosi (1988), “technological progress proceeds through the development of both public elements of knowledge, shared by all actors involved in a certain activity, and private, local, partly tacit, firm-specific, cumulative forms of knowledge”.

In the context of private forms of knowledge and local nature of learning, we believe that the *structure of the network* of relations between producers and users of innovations affects the nature (speed and variety) of the learning processes of firms, their technological performances and the rate of technological progress. It has also been suggested that the use of vertically-related sectors as object of the analysis allows the understanding of (i) transmission of demand and technological impulses between agents that might not have competitive interactions; (ii) processes of innovation and diffusion (Chiaromonte and Dosi, 1993). We believe that the structure of vertically-related sectors shapes the nature of the above processes.

The concept of learning can be usefully analysed by focusing on different factors: interactions between buyers and suppliers, length of the interaction, heterogeneity of relations. The heterogeneity of relations is particularly important when the object of the transaction between buyers and suppliers is a complex product such as the aero-engine. In a complex product, technological efforts may be devoted to different directions. Technological trade-offs may lead to different emphasis on different solutions. Moreover, customers may have differentiated requirements which can be met with idiosyncratic solutions. Heterogeneity of relations represent therefore an opportunity for suppliers of learning by exploring the space of possible technological solutions in multiple directions dictated by customers.

In this work we claim that the processes of technological learning, spillover and competition, which are characteristics of different levels of cohesion of the network (partitioned versus hierarchical), affects the technological competition among suppliers.

Different network structures shape the actual possibility of actors for *learning by interacting* with single or multiple actors. Taking two extreme cases, in hierarchical networks, composed of a core and a periphery, suppliers in the core accumulate technological knowledge by supplying a number of customers; on the other hand, customers related to multiple suppliers learn by using different products of heterogeneous actors. By contrast, in partitioned networks, relations are mainly one-to-one and suppliers learn from a single buyer (and viceversa).

Moreover, in hierarchical networks *learning externalities and spillovers* are more relevant with respect to partitioned networks. In fact, within a core of highly connected buyers and suppliers, spillovers increase with the number of common customers/suppliers for a number of reasons:

- within a core a customer with multiple sourcing improves its specification capability with advantages for all its suppliers;
- innovation from a supplier stimulates the customer to require similar innovations from the other suppliers;
- suppliers with similar positions and technological characteristics have a higher probability of imitating the innovating actors.

Finally, within a core of suppliers related to the same group of customers, it is very likely to observe an intense *competition*.

The paper aims to show that:

1. when the network is hierarchical (composed of a core and a periphery) the formation of the core leads to: equalisation of technical and market opportunities through access to the same customers, various forms of learning by interacting with heterogeneous actors, intense competition and rapid technical progress;
2. in the periphery actors have a higher probability of learning by interacting (imitating) with (from) the core when the technological distance is lower; when technological distance is higher the probability of imitation is lower and decrease further if actors have no relations with the core. They are active in isolated niches of the market where the rate of technical progress is slower;

3. when the network is partitioned cumulative learning in single relations leads to different solutions to technical problems in different couples of vertically-related firms. The opportunities for interaction and spillovers are limited, competition is weaker and the rate of technological progress is slower.

Next section describes the methodologies used in the empirical analysis. Specifically, it reviews the literature on measurement of technical progress, by highlighting the indicators allowing direct measures of technical progress and the technological position of actors. It also describes the measures of vertical networks drawn from social network analysis. Section 4 presents data on the aero-engine and aircraft industries and the statistical analysis for classifying products in clusters on the basis of their technical characteristics. Section 5 discusses the results of the empirical analysis, by linking vertical networks and technometric analysis. Finally section 5 concludes and proposes lines for further research.

3. Measuring technical progress and vertical networks

3.1 Measuring technical progress

The problem of measurement of technical progress and technological positions of firms has a long history and has been tackled by a number of contributions within different approaches. This section discusses some of the contributions attempting to measuring directly the output of innovative activity with the objective of finding appropriate measures of technical frontiers and of technological positions of actors.

In the neoclassical perspective, technical progress was introduced through measures of productivity, which are very far from direct measures of technological attributes of products and from customer perception of technological performance. We share the belief that the relevant object of analysis of technological innovation is the product, as composed of a number of characteristics evolving over time (Lancaster, 1971; Sahal, 1985; Saviotti and Metcalfe, 1984; Trajtenberg, 1990; Grupp, 1998). Innovation on products occurs by improvement (change in the type or value) of their technical characteristic, or by introduction of new characteristics.

The emphasis on the characteristics of products has been introduced within characteristic approach and the Hedonic price method (Lancaster, 1971, 1975; Griliches, 1971), in which it is developed the concept that products are a bundle of characteristics and consumers choose characteristics instead of products. Utility functions have characteristics and not products as arguments. According to this view, the benefit of characteristics for consumers are detected through regression models measuring the contribution of technical characteristics to the formation of product prices. On this basis, Trajtenberg (1990) developed a model for studying product innovation in the CT scanners industry.

However, the use of price for estimating the weight of characteristics presents some difficulties: the approach is based on the assumption that the market is competitive, but in a number of industries price is not determined by the free interplay of supply and demand (Sahal, 1985); data on prices are not always publicly disclosed, and even in the case in which price lists are available, the price of a specific product can change over time (for example because of cost reductions) determining uncertainty in the selection of data. Moreover, the use of economic variables in the evaluation of technical attributes does not allow the "pure" measurement of technology advance (Saviotti and Metcalfe, 1984).

Saviotti and Metcalfe (1984) proposed a useful distinction of product characteristics taking into account the supply and the demand side of the market in *technical* characteristics, incorporated in a product supplied for performing some functions, and *service* characteristics, that is the performances required by users of the product. The product is described by technical and service characteristics and by the *mapping* between the two. More recent contributions use measures of diversity (entropy measure, Weitzman's measure) using data on technical and service characteristics to measure the emergence of new product niches as an indicator of technical progress (Saviotti, 1996; Frenken et al., 1999, 2000). These measures allow the identification of dominant design and product differentiation at the industry level, but are not used to detect technological frontiers and positions of actors.

A few contributions develop technometric measures based on various multi-dimensional functions linking technical parameters for the analysis of technological progress (Sahal, 1985; Dodson, 1985; Martino, 1985), but do not address the analysis of technological competition among actors.

Simpler technometric indicators are proposed by Grupp (1998) to measure directly technical progress. Each product in a market segment is represented by a *k*-tuple of technical characteristics at time *t* which is compared with other *k*-tuples for other products. In each cluster and for each technical characteristics *k* for product/firm *j* it is computed a simple indicator T^t as follows:

$$T_{jk}^{t} = \frac{K_{jk}^{t} - K_{\min k}^{t-1}}{K_{\max k}^{t-1} - K_{\min k}^{t-1}}$$

where

j = 1, 2, …m firms

k = 1, 2, …z technical characteristics

K_{jk}^{t} is the maximum value k of firm j at time t across all its products

$K_{\min k}^{t-1}$ is the worst value of k at time t_0 across all firms j and

$K_{\max k}^{t-1}$ is the best value of k at time t_0 across all firms j.

The T index is 0 when the firm is positioned on the minimum level of the previous period; T is equal 1 if the firm is on the frontier of the previous year; T greater than 1 indicates that the firm has shifted the frontier while T lower than 1 indicates that the firm is below the frontier of the previous year. At t_0 the index is static (i.e. it is calculated taking the value of the firm in t_0), and represents the firm's position at the time it enters the industry or the product group.

We use this index with the assumption that new characteristics or improvements of technical characteristics are introduced after a process of problem solving of techno-economic trade-offs involving users and producers. User-producer interactions allow the suppliers to develop technical attributes which meet performance characteristics required by customers. The problem we address through the analysis of the structure of the network of vertical relations is to understand and measure how the structure of vertical relations between buyers and suppliers affect the rate of technological progress and the intensity of technological competition.

The advantages of this technometric indicator are the following:

- it is dimensionless;
- it is observable over a period of time for detecting technical progress;
- it allows the identification of brands and firms for the analysis of technological positions of actors along the frontier
- it can be used as a simple and direct measure of technical progress, by replacing at the numerator in the formula K_{jk}^{t} by $K_{\max k}^{t}$. In this case a value of the index greater than one indicates technical progress.

Another advantage in using technical parameters of products with respect to other measures of innovation such as patents, is that they allow the identification of technological trajectories and their evolution over time through indicators of output of the innovative activity, which is directly related to the product and not only to technological competencies of firms.

The main problem of this indicator is related to the aggregation of the indexes for each characteristic at the firm or at the product/brand level and the consideration of trade-offs among characteristics. Because the index is dimensionless, weighted averages of the indexes could be a solution. A careful process in the determination of the weights and trade-offs is necessary for reducing the subjectivity of the analysis. This process should involve technical experts and customers.

3.2 Measuring vertical networks

Network analysis has been applied in many fields of social sciences, including economics, sociology, and organisation, for analysing different structures of interactions among agents (individuals, firms, groups of actors, technical artefacts). In the analysis of industries, network concepts and techniques are increasingly used in the field of inter-firm agreements (joint ventures, licensing, technological alliances, consortia and the like) (Powell, 1996; Orsenigo et al, 1998, 2001). We apply network analysis to the study of vertical relations between buyers and suppliers. The network may assume different topologies which can be represented by different network measures. For the purposes of this study, we analyse three structural properties of the network: the *relational intensity*, the *distribution* of the relations across actors and the *position* of actors in the network[1].

For the analysis of vertically-related industries we study bipartite graphs, in which links connect vertices from different sets of actors (buyers and suppliers) and there are no links within each set (Borgatti and Everett, 1997; Asratian et al., 1999). The links in the network are determined by the order of an engine placed by an aircraft company to an aero-engine manufacturer at a given date. The structure of the relations is represented for each year by a biadjacency matrix, whose cells represent the binary variable “a link exists / does not exist”.

We selected the following network measures to study the structural properties of the network: centrality degree, density, *k*-core[2].

At the actor level we compute measures of *centrality degree*. The degree of an actor is defined as the number of links incident with that vertex. The total number of links depends on the network size, that is, on the total number of actors. We normalise the degree for obtaining a more informative index, dividing the degree by the total number of connections occurring in the network. This index seizes on the comparison of the relational intensity among the actors, by measuring the share of total relations in which each actor is involved.

The *density* is essentially a count of the number of links actually present in a graph, divided by the maximum possible number of links in a graph of the same size. Density is a synthetic measure

[1] The network methodology exposed in this section has been drawn from previous papers where it is developed more extensively (Bonaccorsi Giuri 2001a, 2001b).
[2] Measures of density and *k*-cores, bi-components and cut-points are computed by using the software Ucinet 5 (Borgatti et al., 1999).

of network structure which provides information about the group *relational intensity* and the cohesion of a graph, but does not include information about the variability among actor degrees.

We also calculate a measure at the sub-graph level, to analyse the *distribution of the relations* across actors. In particular we study the number and size of *k*-cores, which allow to detect the presence of cohesive sub-groups. A *k*-core is a connected maximal induced sub-graph which has minimum degree greater than or equal to *k* (Wasserman and Faust, 1995). Each member of a *k*-core is related to at least *k* other actors on the other set. We calculate the number of *k*-cores in the network for every possible value of *k* and for each year of their life.

For *k*=1 the number of cores indicates the degree of *partition* of a network. The higher the number, the higher the degree of partition of the network, as the network can be separated in sub-graphs without deleting any vertex. Intuitively, a partitioned network is composed of isolated sub-groups of vertically-related actors.

The presence of cores with degree greater than or equal to *k* denotes cohesiveness of a graph, that is the distribution of relations across actors is not dispersed but is concentrated in sub-groups of intensely connected actors. In particular, a network characterised by a connected core and a periphery of disconnected actors can be defined as *hierarchical*[3].

4. The aero-engine industry

4.1 Data

The objects of the empirical analysis are the commercial turboprop and jet aero-engine industries since their birth, respectively in 1948 and 1958 to 1997. The choice of the aero-engine industry has a number of reasons:

- well-defined brands and generation of products;
- availability of complete directory of data;
- existence of a stable set of technical and performance characteristics representing the product over the history of the industry;
- well-defined vertically-related objects (aero-engines and aircraft) and firms (buyer and suppliers are always separated firms, as no vertical integration occurs in the industry).

The empirical analysis is based on two databases.

The *Atlas Aviation Database* contains all transactions (orders) occurring from 1948 to 1997 between engine manufacturers, aircraft manufacturers and airline companies in the market for commercial jet and turboprop aircraft. For each transaction the aircraft and engine product version is specified. These data are used for calculating measures of structure of the network of vertically-related firms and measures of position of actors in the network. The unit of analysis is the transaction of engines occurring between an engine and an aircraft manufacturer each year.

The *AirTech* database contains 16 technical parameters for 114 jet engine versions and 11 technical parameters for 76 turboprop engine versions and two basic parameters for each aircraft included in the Atlas database (Table 1). The AirTech database has been built by using several sources of data: *Jane's All the World Aircraft* 1950-1998, *Jane's Aero-engines* 1997, *Flight International* 1970-2000, *Aviation Week and Space Technology* 1970-2000, engine and aircraft companies web sites, company reports, product brochures, technical data provided by a major airline company, phone contacts with technical and information offices of two of the larger aero-engine companies.

Further information and details have been drawn from publications on the history of the aviation technology and on the structure of the aircraft and aero-engine industries (among others Miller and Sawers, 1968; Phillips, 1971; Constant, 1980; Mowery and Rosenberg, 1982; Vincenti, 1990; Garvin, 1998).

From the list of parameters exhibited in Table 1 we selected for the jet 5 technical characteristics (weight, length, diameter, thrust, airflow) and 3 technical performance parameters (BPR, OPR, SFC), or service characteristics with the terminology of Saviotti and Metcalfe (1984), whose direction of advance is clearly defined for the overall industry (BPR, OPR) and for each segment (SFC). In the turboprop we selected 4 technical characteristics (weight, lenght, width, power) and 2 technical performance parameters (Pressure ratio, SFC). The choice of technical parameters and the distinction in characteristics and performance parameters has been validated through interviews with aeronautical engineers and with managers of the purchasing division of a major airline company[4]. Descriptive statistics on the characteristics are reported in Appendix1, Table A1.

In other works technical and service characteristics are used to study the evolution of variety in industries and the emergence of dominant designs and product differentiation at the industry level (Saviotti, 1996; Frenken et al., 2000). We use cluster analysis for classifying firms and products within product classes with the aim of identifying technological frontiers and position of firms along the frontier.

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[3] The notion of *hierarchy* in vertical networks is different from a *tree*-structure of relations among actors which is not characteristic of networks connecting two sets of actors. In this case a *hierarchical* network denotes the presence of a *inner core* and a *periphery,* both composed of actors from the two sets, i.e. buyers and suppliers.

[4] Some of them, like thrust, can be difficult to classify because they can be considered technical or performance characteristics, depending on the level of education of customers.

Table 1. List of product characteristics

Industry	Type of characteristics	Characteristics
JET		
Aero-engine	Technical	Compressor
Aero-engine	Technical	Engine type (output)
Aero-engine	Technical	Combustor type
Aero-engine	Technical	N° fans
Aero-engine	Technical	N° LP compressors
Aero-engine	Technical	N° HP compressors
Aero-engine	Technical	N° of turbines
Aero-engine	Technical	N° HP turbines
Aero-engine	Technical	Air flow - lb/sec
Aero-engine	Technical	Length – inch
Aero-engine	Technical	Diameter – inch
Aero-engine	Technical	Weight-dry - lb
Aero-engine	Technical	Thrust TO – lb
Aero-engine	Service	BPR (By pass ratio)
Aero-engine	Service	OPR (Overall pressure ratio)
Aero-engine	Service	SFC (Specific Fuel Consumption) TO - lb/hr/lb
Aircraft	Service	Seats
Aircraft	Service	Range – nm
TURBOPROP		
Aero-engine	Technical	Compressor
Aero-engine	Technical	Engine type
Aero-engine	Technical	Combustor type
Aero-engine	Technical	Number of turbine
Aero-engine	Technical	Prop drive
Aero-engine	Technical	Fan/compressor
Aero-engine	Technical	Length - inch
Aero-engine	Technical	Width – inch
Aero-engine	Technical	Weight–dry – lb
Aero-engine	Technical	Power T-O – ehp
Aero-engine	Service	Pressure ratio at max power
Aero-engine	Service	SFC (Specific fuel consumption) T-O - lb/h/ehp
Aircraft	Service	Seats
Aircraft	Service	Range - nm

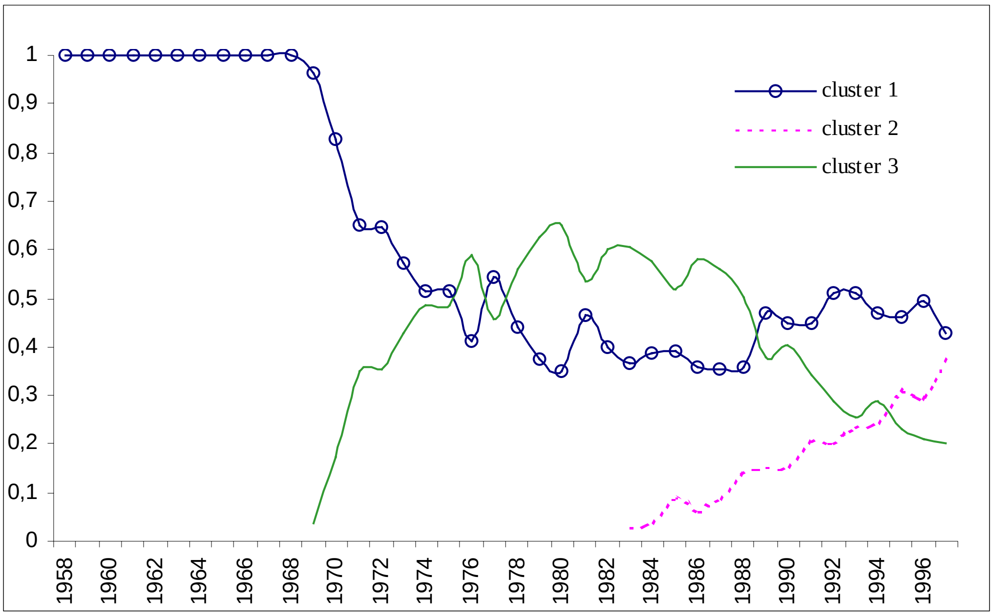
In the jet, data on the selected 5 technical characteristics of aero-engines have been used to obtain a segmentation of the industry by classifying 114 engine products into three sub-groups through cluster analysis. In the turboprop 76 engine products have been classified in two sub-groups. The variables have been previously standardised for avoiding effects of the choice of the units of measures in the determination of the clusters.

Cluster analysis can be carried out with two methodologies: hierarchical and partitioning (Kaufman and Rouseeuw, 1990; Everitt, 1993). We apply hierarchical clustering because it is more appropriate when the number of observations is not very large (less than 200). Within hierarchical clustering, we used the agglomerative technique of classification of data. It is an iterative procedure used to identify relatively homogeneous groups of cases based on the selected characteristics, using an algorithm that starts with each case in a separate cluster and agglomerates clusters step by step until only one is left. The possible methods of aggregation are based on different measures of distance between observations and groups. The choice of the method depends on the expected equality or inequality of size and variance of clusters and on the expected shape of clusters (spherical or elongated). We used the complete linkage method (also known as furthest neighbour) because of the different size and variance of clusters and of the roughly spherical shape of clusters. The dissimilarity between groups is defined by the largest distance between cases of two clusters.

The determination of the number of clusters in the jet has been based on tests of the ANOVA for variables with approximately normal distribution and homogeneity of variance between groups (LENGHT) and non homogeneity of variance (DIAMETER). For variables with non normal distribution (WEIGHT, AIRFLOW AND THRUST) we used the non parametric Kruskal Wallis test to verify the presence of significant differences between the means of clusters. All tests supported the grouping of observations in three clusters (see in Appendix 1, Table A2 for the classification of engines in clusters and Table A3 for descriptive statistics of the service characteristics of products within clusters). Cluster 1 represents the smaller segment of the market, including the first turbojets introduced at the birth of the industry, the turbofans introduced at the beginning of the 1960's in substitution of the turbojets, the second generation of turbofans and the small regional jets of the 1990's. Cluster 2 includes larger size-engines while cluster 3 includes the largest engines of the three big players, which power very large aircraft.

The size of each cluster in terms of market shares is shown in Figure 1.

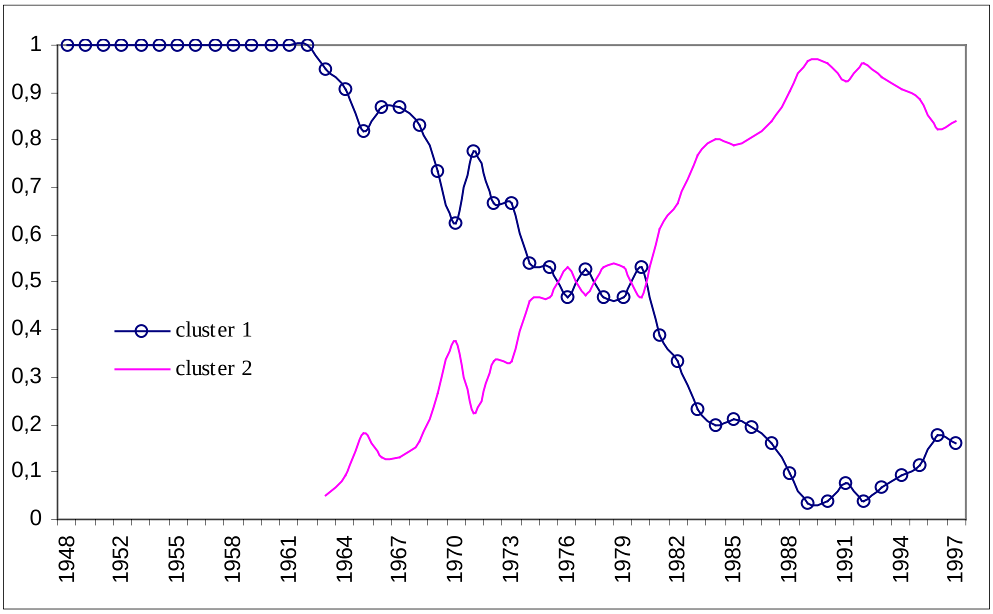
Figure 1. Market shares of clusters - JET



In the turboprop the determination of the number of clusters has been based on ANOVA and T test (equivalent to ANOVA for two independent samples) for variables with approximately normal distribution and homogeneity of variance between groups (WEIGHT). For variables with non normal distribution (length, width, thrust) we used the non parametric Kruskal Wallis and Mann-Withney test (equivalent to Kruskal Wallis test for two independent samples) to verify the presence of significant difference between the means of clusters. ANOVA and Kruskal Wallis tests did not provide significant results for a classification of engines in more than two clusters, while all other tests supported the grouping of observations in two clusters (the classification of engines in clusters and the descriptive statistics of SFC and PR within clusters are reported in Appendix 1, Table A2 and A4).

Cluster 1 includes all engine powering regional aircraft with more than 50 seats, while cluster 2 groups engines for smaller aircraft. It experienced a rapid growth during the 1980s, when the air transport deregulation fuelled the growth of the smaller size of the turboprop regional market (Meyer and Oster, 1984; Bailey et al, 1985; Button and Stough, 2000). Conversely, cluster 1 witnessed a decline of its market share with respect of cluster 2, also because of the recent appearance of small jets in the regional market.

Figure 2. Market shares of clusters - TURBOPROP



This classification of engines within clusters has been supported by qualitative information drawn from specialised press, company reports and publications on the history and structure of the aviation industry, and validated through interviews with technical experts.

Within each segment the technometric indicators T of technical progress developed by Grupp (1998) have been computed to identify technological trajectories for OPR, BPR and SFC at the jet industry level, and for PR and SFC at the turboprop industry level, while indicators of progress and positions of actors along the technological frontiers have been computed within each segment for these performance parameters.

Data on technical parameters were available as attributes of the product versions, whose date of introduction and sales were also available. Their observation over time has been obtained by referring to the existence in life of an engine (as indicated by the presence in the fleets of airlines). We preferred to consider the existence in fleet than the date of introduction of the product or the date of sales of the product for studying the technical progress, as it is more continuous and does not depend on purchasing decisions which occur at discrete points in time. In fact, the introduction of new products at a time t is an innovation that may move the frontier upwards, but the existence of the product in fleets allows the persistence of the data over time.

5. Empirical analysis

5.1 The jet industry

This section presents the result of the empirical analysis in the jet aero-engine industries and provide a discussion of the hypothesis through the mapping of the technometric analysis on the network structure and evolution over time.

It is important to specify that the analysis of the network has been carried out at the industry level, while the technometric analysis at the product class level, as resulted by the statistical cluster analysis. Product classes are not independent, as companies operating in more than one product class enjoy economies of scope and economies of learning. The assumption is that the analysis of network at the product class level would neglect those economies at the total industry level. On the contrary, with respect to the technometric analysis, the separation in segment is needed because of their technological diversity. In fact, technological constraints related to the size of the engines lead to the existence of technological frontiers at the segment level. Table 2 synthesises the presence of companies in the product classes. All companies are present in cluster 1, while only Pratt & Whitney, Rolls Royce and General Electric developed engines of larger size, competing in the other two segments.

In this section we discuss the empirical analysis with the hypothesis that the structure of the overall network and the central position of actors in the network affect the technological competition at the supplier level.

Table 2. Firms in clusters

Industry	Label	Firm	CLUSTER 1	CLUSTER 2	CLUSTER 3
Aero-engine	AE	Allison	✔		
	CI	CFM International	✔		
	GE	General Electric	✔	✔	✔
	IA	International AeroEngines	✔		
	PW	Pratt & Whitney	✔	✔	✔
	RR	Rolls Royce	✔	✔	✔
	TX	Textron	✔		
Aircraft	ARO	Aerospatiale (-Alenia)	✔		
	AIR	Airbus	✔	✔	✔
	COM	Comet	✔		
	BOE	Boeing	✔	✔	✔
	BOM	Bombardier	✔		
	BAE	British Aerospace	✔		
	DAS	Dasa	✔		
	EMB	Embraer	✔		
	FOK	Fokker	✔		
	HAW	Hawker Siddeley	✔		
	LOC	Lockheed	✔		✔
	MDC	Mc Donnell Douglas		✔	✔
	ROM	Rombac	✔		
	VFW	VFW	✔		
	VIC	Vickers	✔		

Table 3 summarises the network measures at the group, sub-group and actor level for each year of the period, while the network structure in the jet industry at 4 dates (1960-1970-1985-1997) is shown in Figure 3. The measures showed in Table 3 are number of actors (*actors*), level of relational density of the network (*density*), number of *k*-cores with *k*=1 (*1-core*), number of *k*-cores with *k*=2 (*2-core*), number of vertices in the core with *k*=2 (*2-core size*), normalised centrality degree of actors for the aero-engine firms (*AE centr., CI centr…)*.

At the aggregate level, we observe that the level of density in the jet is oscillating over time, depending on the entry of actors with a small number of relations (declining pattern) and on the increasing relational intensity among established buyers and suppliers (growing pattern). The analysis at the sub-graph level provides details on the distribution of relations across sub-groups of actors. In particular, it gives evidence of the degree of partition and of the formation of a hierarchical structure of the network.

The network is composed of only one or two sub-graphs over all its life, except in the last three years, in which there are three *1*-cores, and the larger partition is composed of 10 firms operating in all three clusters. The other two partitions are two pairs of vertically-related firms in the market for small regional jets, which are part of cluster 1.

The number of 2-cores denotes the degree of hierarchisation of the network. The network assumes a *hierarchical* configuration as it is possible to identify a cohesive core in which the actors have degree greater than or equal to 2. The core emerged during the first stage of the industry life and was initially composed of 4 actors in cluster 1 (shaded area in figure 5, 1960). The entry of new actors at the end of the 1960s and at the beginning of the 1970s destabilised the network and the core. The intensification of the relational activities of entrants and incumbents led again to the emergence of a core which expanded during the industry evolution. In fact, as evident from the table, the number of actors grew from 4 in 1975 to 8 in 1997, therefore a larger part of actors entered the core. The core was composed of incumbent engine suppliers in clusters 1, 2 and 3 and of major aircraft manufacturers operating in multiple sourcing. On the other hand, a periphery was also created in the network, which was composed of actors with degree equal to 1, that is aircraft manufacturers in single sourcing and engine suppliers in the regional market, all operating in cluster 1. The network was also partitioned in the last three years, as there were three subgroups, two of them in the regional market (Allison-Embraer and Textron-British Aerospace), and the other containing the *2*-core.

The normalised centrality degrees show that the first movers Rolls Royce and Pratt & Whitney, former relational leaders, lose their central positions while maintaining a high number of relations. This is due to the increasing centrality of other actors which also join the core. In the last two decades the positions of actors in the core tend to equalise, while a smaller value is observed for actors at the periphery.

Figure 3. The jet network

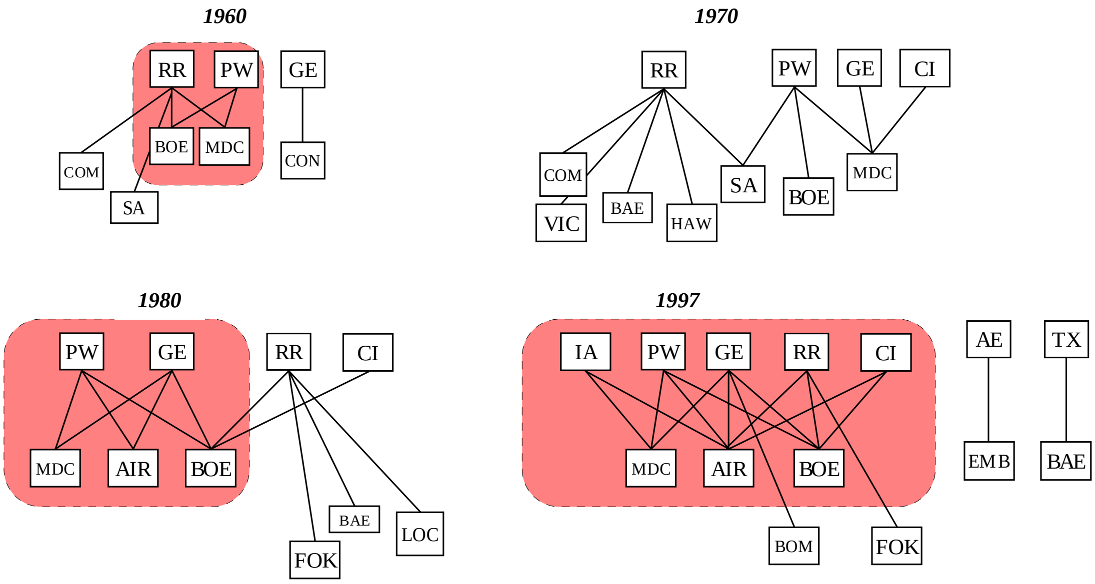


Table 3. Network measures

Year	actors	density	number 1-core	number 2-core	size 2-core	AE centr.	CI centr.	GE centr.	IA centr.	PW centr.	RR centr.	TX centr.
1958	4	0.50	2	-	-		0.00			0.50	0.50	
1959	6	0.50	2	-	-		0.00			0.50	0.50	
1960	8	0.47	2	1	4		0.00	0.14		0.29	0.57	
1961	8	0.47	2	1	4		0.00	0.14		0.29	0.57	
1962	8	0.53	2	1	5		0.00	0.13		0.38	0.50	
1963	10	0.43	2	1	4		0.00	0.11		0.22	0.67	
1964	11	0.42	2	1	4		0.00	0.10		0.30	0.60	
1965	10	0.43	2	1	4		0.00	0.11		0.33	0.56	
1966	8	0.67	1	1	4		0.00			0.38	0.63	
1967	10	0.48	1	1	4		0.10			0.30	0.60	
1968	10	0.43	1	1	4		0.11			0.33	0.56	
1969	10	0.43	1	-	-		0.11			0.33	0.56	
1970	11	0.36	1	-	-		0.10	0.10		0.30	0.50	
1971	10	0.38	2	-	-		0.13	0.13		0.38	0.38	
1972	12	0.36	2	-	-		0.10	0.10		0.30	0.50	
1973	13	0.38	2	-	-			0.22		0.33	0.44	
1974	13	0.38	2	-	-			0.22		0.33	0.44	
1975	13	0.38	2	1	4		0.08	0.25		0.25	0.42	
1976	12	0.42	2	1	4			0.30		0.20	0.50	
1977	12	0.46	1	1	6		0.15	0.23		0.15	0.46	
1978	12	0.43	1	1	4		0.08	0.25		0.17	0.50	
1979	10	0.51	1	1	4		0.11	0.33		0.22	0.33	
1980	10	0.52	1	1	5		0.09	0.27		0.27	0.36	
1981	11	0.44	1	1	5		0.08	0.25		0.25	0.33	0.08
1982	12	0.41	1	1	5		0.08	0.23		0.23	0.38	0.08
1983	12	0.35	2	1	4		0.09	0.27		0.18	0.36	0.09
1984	12	0.44	1	1	5		0.08	0.25		0.25	0.33	0.08
1985	12	0.36	2	1	5		0.08	0.23		0.31	0.31	0.08
1986	12	0.35	2	1	4		0.09	0.27		0.18	0.36	0.09
1987	11	0.44	2	1	6		0.17	0.25		0.25	0.25	0.08
1988	11	0.49	2	1	6		0.18	0.27		0.27	0.18	0.09
1989	12	0.49	2	1	6		0.17	0.25	0.08	0.25	0.17	0.08
1990	12	0.44	2	1	6		0.15	0.23	0.08	0.23	0.23	0.08
1991	11	0.49	2	1	6		0.17	0.25	0.08	0.25	0.17	0.08
1992	12	0.44	2	1	6		0.15	0.31	0.08	0.23	0.15	0.08
1993	12	0.44	2	1	6		0.15	0.31	0.08	0.23	0.15	0.08
1994	12	0.44	2	1	6		0.15	0.31	0.08	0.23	0.15	0.08
1995	14	0.39	3	1	8	0.06	0.13	0.25	0.13	0.19	0.19	0.06
1996	14	0.39	3	1	8	0.06	0.13	0.25	0.13	0.19	0.19	0.06
1997	14	0.39	3	1	8	0.06	0.13	0.25	0.13	0.19	0.19	0.06

Figures 4a,b,c depict the frontier at the industry level and at the firm level for the three technical performance parameters BPR, OPR and SFC[5]. The values represent the maximum reached by the firms at each year of the period, and the industry frontier is the absolute maximum value observed each year. In the case of SFC the frontier is the minimum absolute value. However, the values of

[5] Technical data for General Electric from 1960 to 1965 are not available. We could find data on technical parameters but not on the presence of its engines in fleets, as they were not present in the Atlas Aviation Database. However from other sources we found that the engine was sold in a very small number of units and for a short period of time, and the interruption of the production was followed by the exit of the producer from the commercial market.

SFC at the overall industry level cannot be considered a proper frontier, because the level of specific fuel consumption is dependent on the product classes. Figure 3c represents therefore a statistics of the minimum level at an aggregate level.

At this aggregate level of industry the graphs suggest that technological innovations occur quite discontinuously, and are introduced by different actors over time. Once a shift of the frontier occurs, all follower approach the frontier with differentiated lags. In some cases firms never approach the frontier, maintaining isolated patterns, as for example for Allison and Textron, operating at the periphery of the network.

Figure 4a. Technical frontier of industry and firms - BPR

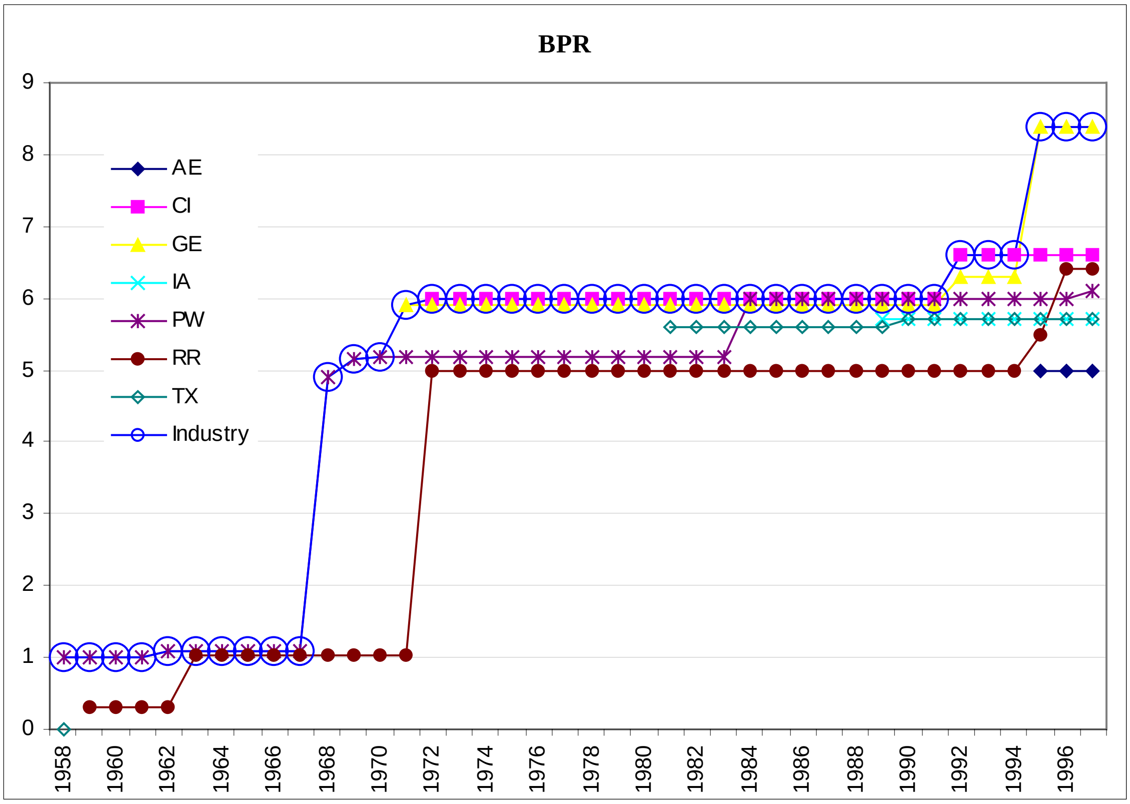


Figure 4b. Technical frontier of industry and firms - OPR

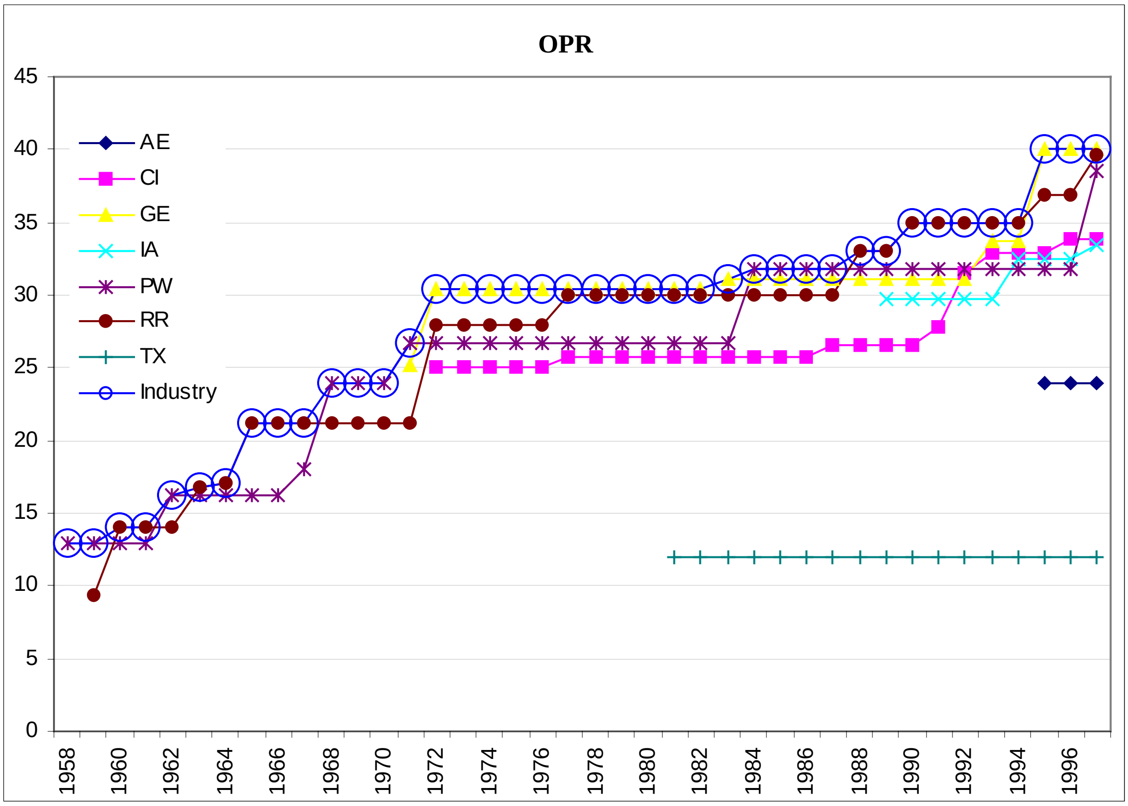
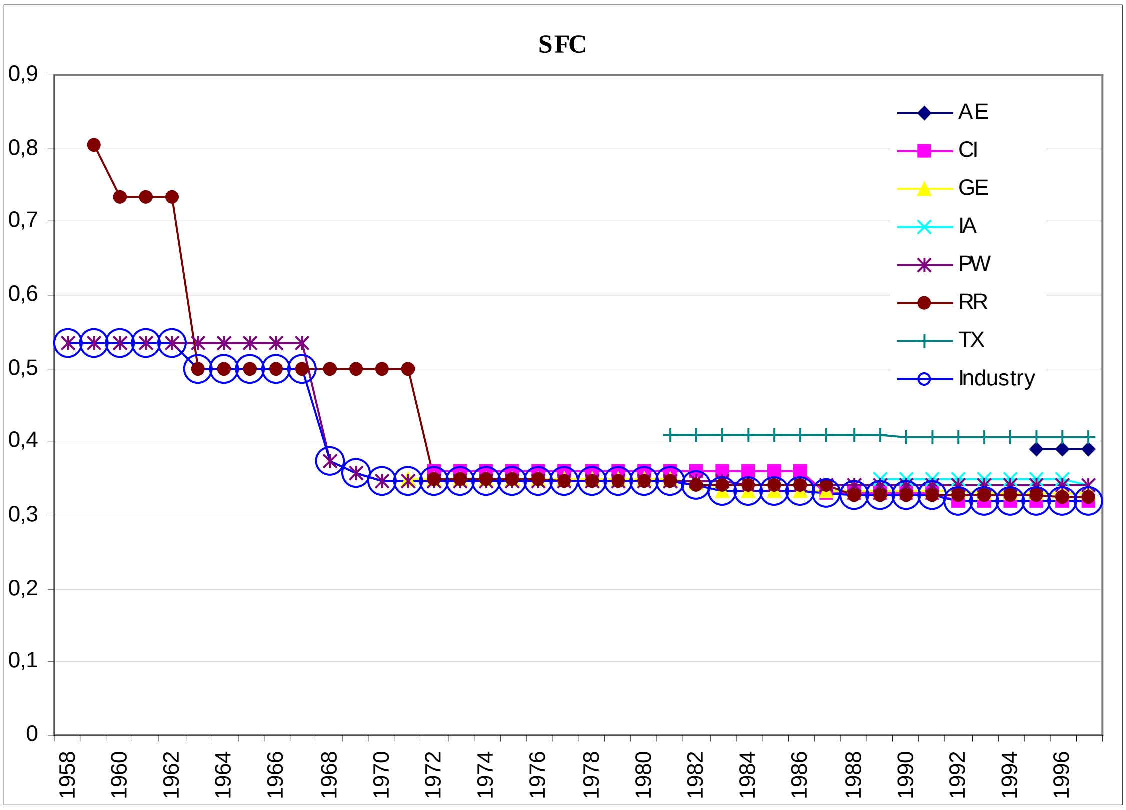


Figure 4c. Technical frontier of industry and firms - SFC



The technological competition at the segment level is analysed through the computation of the index *T* for each parameter at the firm level for every year of the period analysed (see Figures 5a and 5b). T values greater than one point out shifts of the frontier, while T values lower than one indicate that the companies are below the frontier of the previous period.

In cluster 1 technological advances are introduced by different companies over time. Rolls Royce and Pratt & Whitney were on the frontier until the beginning of the 1970s. Subsequently major technological innovations have been introduced by CFM International and by International Aeroengines, while the distance from the frontier of the other actors increased. Textron is positioned well below the frontier, confirming the independent patterns of technological evolution and competition at the periphery of the network, already observed at an aggregate level. In this work we are studying in detail the frontier for single parameters, without considering trade-offs or correlation among them. The determination of the weights of the parameters through interviews with expert of the supply and of the demand side of the industry, and the estimation of a multi-parameter frontier is the object of an ongoing research. However, the analysis for single parameters has the advantage of showing in detail the different solutions introduced by suppliers, which result in improvements of different parameters according to the specific requirements of customers and the specific learning path of suppliers.

Cluster 2 is characterised by a number of jumps in the frontier most of them introduced by General Electric. Rolls Royce introduce innovations in BPR and OPR in the same year as General Electric. T values are greater than one but lower than the values reached by General Electric. In SFC we observe the substitution of the technological leaders (GE and RR). Pratt & Whitney is a follower in this cluster. T values reach the minimum levels in all three parameters and tend to approach the frontier in the last two years.

Cluster 3 is very interesting as it shows changes of technological leadership between all three players in each characteristics. In BPR the sequence is PW-GE-PW, in OPR is PW-GE-PW-RR, in SFC it is PW-RR with an innovation of GE with T-value greater than one but lower than RR. Technological competition is clearly very intense as there is no single technological leader. The characteristics of interactive learning and learning from heterogeneity within the core of the network confirm that there are different solutions to idiosyncratic requirements of customers. In fact, innovations occurs over time in different parameters by different companies. Suppliers solve differently technological trade-offs depending on their positions and on the position of customers. In fact, if also the customer is central in the network, its specification capabilities increase and the possibilities of spillovers among suppliers through common customers increase as well.

When learning is interactive and depends on the specific buyer-supplier relations, heterogeneity of relations multiply the opportunities for learning and introducing new technological solutions, which may be different among players because of the different specific requirements. At the same time, all suppliers have to follow innovation by competitors to stay on the market.

Technological leadership is not only dependent on time, but on time and relational position. This is evident by observing the lost of the leadership of RR and PW in cluster 1.

At the periphery of the network we observe that Allison and Textron in cluster 1 follow separated trajectories. They are always below the frontier but this suggests that they compete in isolated niches of the market. It is also interesting to note that Rolls Royce, one of the former leaders in cluster 1, in 1970 has a number of relations with customers in single sourcing and in 1980 is out of the core, being its customers at the periphery except Boeing. This suggests the opportunities of learning from heterogeneity, but also a fragmentation of efforts in different relations, where customers in single sourcing are not "experienced", do not act as bridges for spillovers of knowledge and do not incentive competition among suppliers.

Figure 5a. Index T – cluster 1, cluster 2

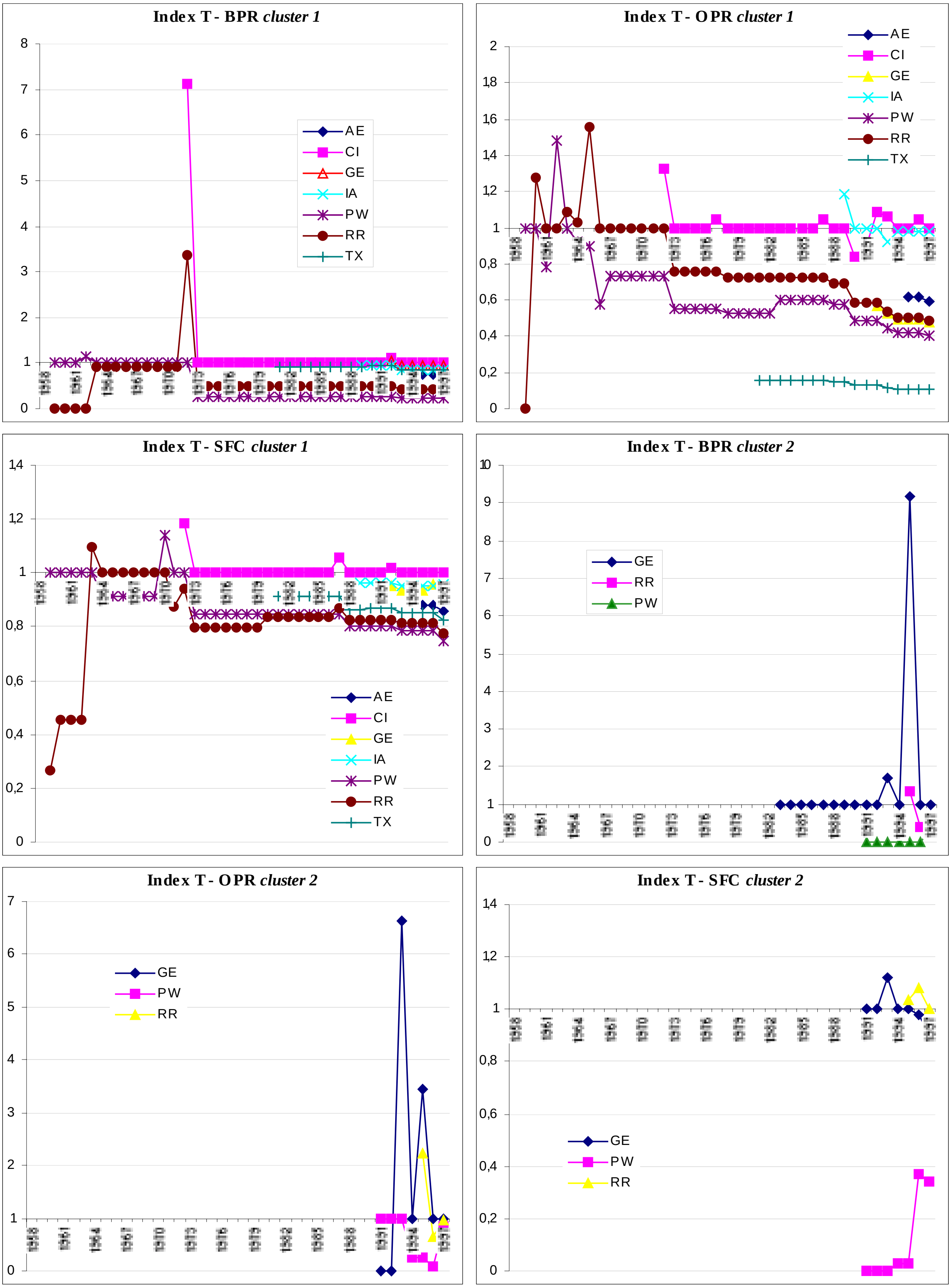
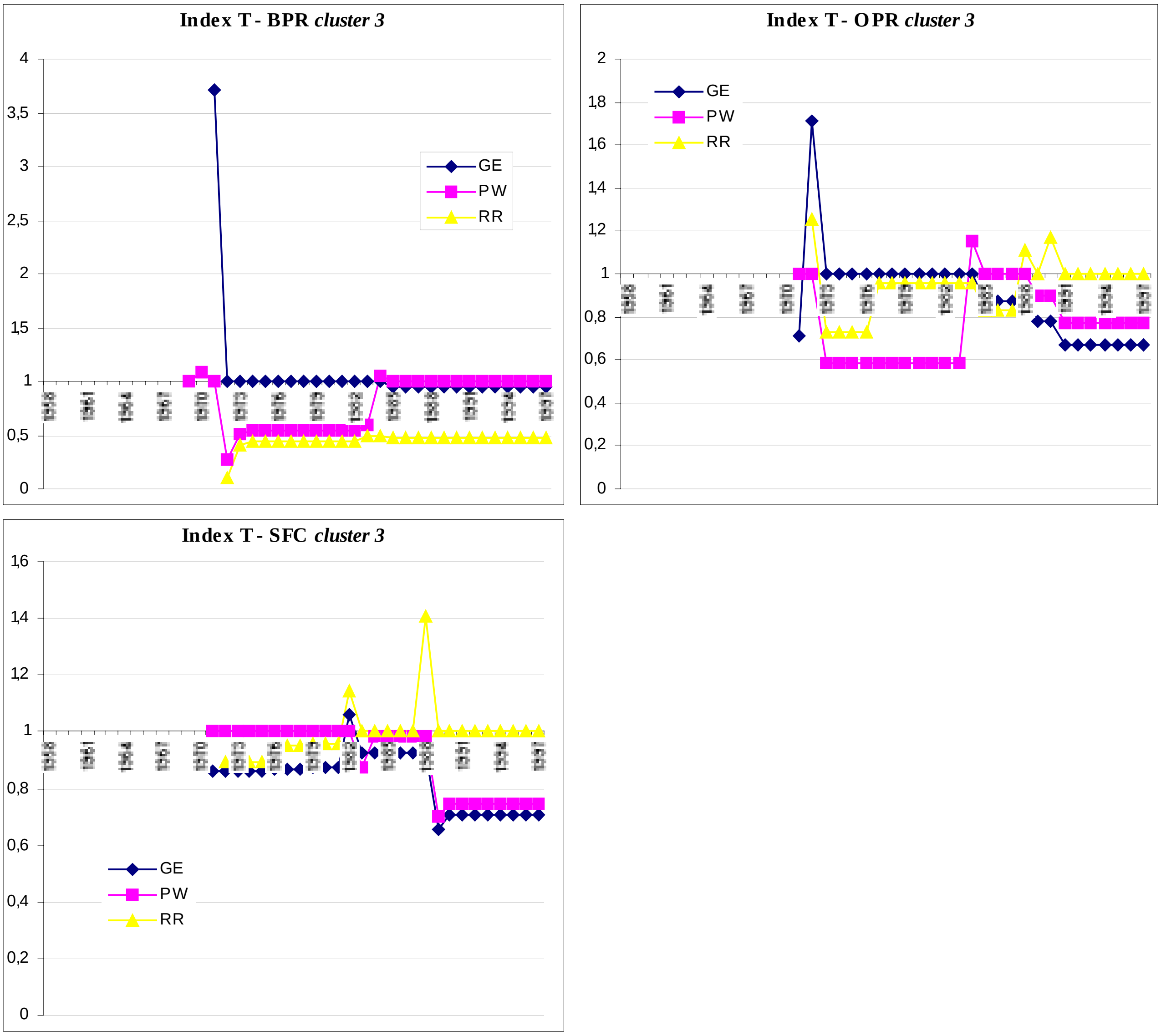


Figure 5b. Index T – cluster 3



5.2 *The turboprop industry*

The turboprop industry presents some interesting differences with respect to the jet industry.

According to the previous analysis, the industry is composed of two product classes. Table 4 shows the presence of aircraft and aero-engine firms in clusters. Except for General Electric and Pratt & Whitney, all aero-engine companies operate in only one product group. In the aircraft industry 6 out of 20 firms operate in two market segments.

Table 4. Firms in clusters

Industry	Label	Firm	CLUSTER 1	CLUSTER 2
Aero-engine	AE	Allison	✓	
	GA	Garrett		✓
	GE	General Electric	✓	✓
	PW	Pratt & Witney	✓	✓
	RR	Rolls Royce	✓	
	TU	Turbomeca		✓
	WA	Walter		✓
	WJ	Dongan	✓	
Aircraft	ARO	Aerospatiale (-Alenia)	✓	✓
	BAE	British Aerospace	✓	✓
	BEE	Beech		✓
	CAS	Casa		✓
	CON	Convair	✓	
	DHC	De Havilland Canada	✓	✓
	EMB	Embraer		✓
	FAI	Fairchild	✓	
	FOK	Fokker	✓	✓
	HAN	HP Herald	✓	
	HAW	Hawker Siddeley	✓	
	IPT	IPTN	✓	
	LET	Let		✓
	LOC	Lockheed	✓	
	NAM	Namco	✓	
	NOR	Nord		✓
	SAA	Saab	✓	✓
	SHO	Shorts		✓
	VIC	Vickers	✓	
	YUN	Yunshuji Xian	✓	✓

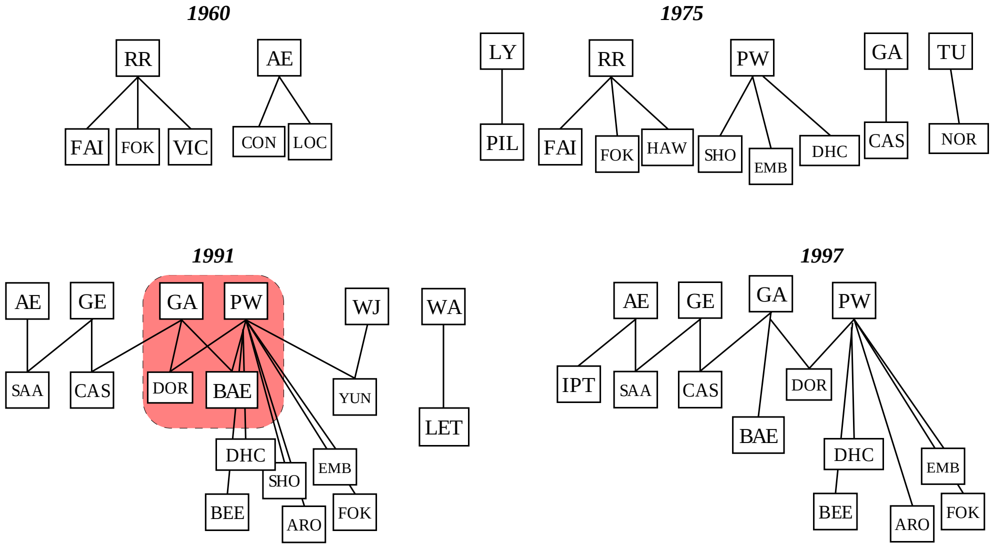
With respect to the structure of the network (figure 6, table 5), in the turboprop industry:

- the level of relational density is lower than in the jet;
- the degree of partition of the network is higher (the number of 1-cores is 6 in 1977), although reducing in the last two decades;
- the network is not hierarchical, as a 2-core composed of 4 actors emerges in 1991 and dissolves in 1995 and there are not other evidences of a formation of a sub-group of connected actors;
- relations among actors are mainly one-to one and sparse;
- on the supply side there is always a relational reader. The level of actor centrality shows in fact for Rolls Royce, the first mover in cluster 1, a very high but declining trend over time, while for Pratt & Whitney, operating mainly in cluster 2, a growing level of centrality;
- on the demand side there are not relational leaders, and customers of relational leaders are mainly in single sourcing.

Table 5. Network measures

Year	actors	density	number 1-core	number 2-core	size 2-core	AE centr.	GA centr.	GE centr.	PW centr.	RR centr.	TU centr.	WA centr.
1953	2	1,00	1	-	-	-	-	-	-	1	-	-
1954	2	0,50	1	-	-	-	-	-	-	1	-	-
1955	5	1,00	2	-	-	0,33	-	-	-	0,67	-	-
1956	6	0,50	1	-	-	0,00	-	-	-	1,00	-	-
1957	7	0,50	2	-	-	0,33	-	-	-	0,67	-	-
1958	8	0,50	2	-	-	0,20	-	-	-	0,80	-	-
1959	8	0,50	2	-	-	0,20	-	-	-	0,80	-	-
1960	8	0,50	2	-	-	0,40	-	-	-	0,60	-	-
1961	8	0,58	2	-	-	0,33	-	-	-	0,67	-	-
1962	9	0,33	2	-	-	0,29	-	-	-	0,71	-	-
1963	11	0,38	3	-	-	0,25	-	-	-	0,63	0,13	-
1964	10	0,25	2	-	-	0,13	-	-	-	0,75	0,13	-
1965	13	0,31	3	-	-	0,10	-	0,10	0,10	0,60	0,10	-
1966	13	0,29	2	-	-	0,10	-	0,00	0,20	0,60	0,10	-
1967	13	0,28	2	-	-	0,10	-	0,10	0,20	0,50	0,10	-
1968	13	0,26	2	-	-	0,09	-	0,09	0,18	0,55	0,09	-
1969	12	0,30	3	-	-	0,11	-	0,11	0,22	0,44	0,11	-
1970	10	0,29	3	-	-	-	-	0,17	0,17	0,50	0,17	-
1971	10	0,23	3	-	-	-	-	0,14	0,14	0,57	0,14	-
1972	13	0,25	4	-	-	-	-	0,11	0,22	0,44	0,11	-
1973	13	0,25	4	-	-	-	-	-	0,29	0,43	0,14	-
1974	15	0,20	4	-	-	-	0,13	-	0,25	0,50	0,13	-
1975	15	0,21	5	-	-	-	0,11	-	0,33	0,33	0,11	-
1976	14	0,16	4	-	-	-	0,10	0,10	0,40	0,20	0,10	-
1977	16	0,23	6	-	-	0,09	0,09	0,09	0,36	0,18	0,09	-
1978	14	0,23	4	-	-	0,13	0,13	0,13	0,38	0,25	-	-
1979	13	0,29	4	-	-	-	0,13	0,13	0,38	0,25	-	-
1980	13	0,28	3	-	-	-	0,14	0,14	0,43	0,29	-	-
1981	14	0,24	3	-	-	-	0,22	0,11	0,44	0,22	-	-
1982	16	0,22	3	-	-	-	0,25	0,08	0,33	0,25	-	0,08
1983	17	0,16	4	-	-	-	0,27	0,09	0,36	0,18	-	0,09
1984	21	0,21	5	-	-	-	0,19	0,06	0,44	0,13	-	0,06
1985	21	0,22	3	-	-	-	0,19	0,13	0,44	0,13	-	0,06
1986	21	0,27	2	-	-	-	0,19	0,19	0,44	0,06	-	0,06
1987	21	0,22	1	-	-	-	0,20	0,20	0,47	0,07	-	0,00
1988	21	0,21	2	-	-	-	0,18	0,18	0,47	0,06	-	0,06
1989	19	0,21	3	-	-	-	0,19	0,13	0,50	-	-	0,06
1990	19	0,24	3	-	-	-	0,19	0,13	0,50	-	-	0,06
1991	20	0,22	2	1	4	0,06	0,18	0,12	0,53	-	-	0,06
1992	19	0,34	3	1	4	0,06	0,18	0,12	0,53	-	-	0,06
1993	18	0,34	1	1	4	0,00	0,20	0,13	0,60	-	-	0,07
1994	18	0,27	1	1	4	0,07	0,20	0,13	0,60	-	-	0,00
1995	18	0,25	2	1	4	0,13	0,20	0,13	0,47	-	-	0,07
1996	16	0,33	2	-	-	0,14	0,21	0,14	0,43	-	-	-
1997	16	0,33	1	-	-	0,15	0,23	0,15	0,46	-	-	-

Figure 6. The turboprop network



With respect to the technological analysis it is evident from figure 7a and 7b that the picture is quite different from the one observed in the jet. In fact in the turboprop industry many companies follow separated technological trajectories and never approach the frontier. In the case of SFC, the technological frontier moves downward discontinuously, some companies attempts to come near the frontier with long lags with respect to the technological innovator, while other firms, including the first mover and former relational leader Rolls Royce, never move towards the frontier and maintain a stable horizontal trajectory. Allison, second mover at the birth of the industry, only innovates in the 1990s becoming technological leader in terms of SFC. General Electric enters the industry introducing an innovating product in the 1960s, while Pratt & Whitney slowly tends to come close to the frontier, by introducing a number of innovative products but never producing a shift of the technological frontier. After the 1980s all companies maintains stable trajectories.

The picture of the evolution of the Pressure Ratio is very similar, showing innovations by General Electric and Pratt & Whitney approaching the frontier only in 1997, an innovation of Allison in the 1990s and stable independent trajectories below the frontier for the other companies.

Figure 7a. Technical frontier of industry and firms – Pressure Ratio

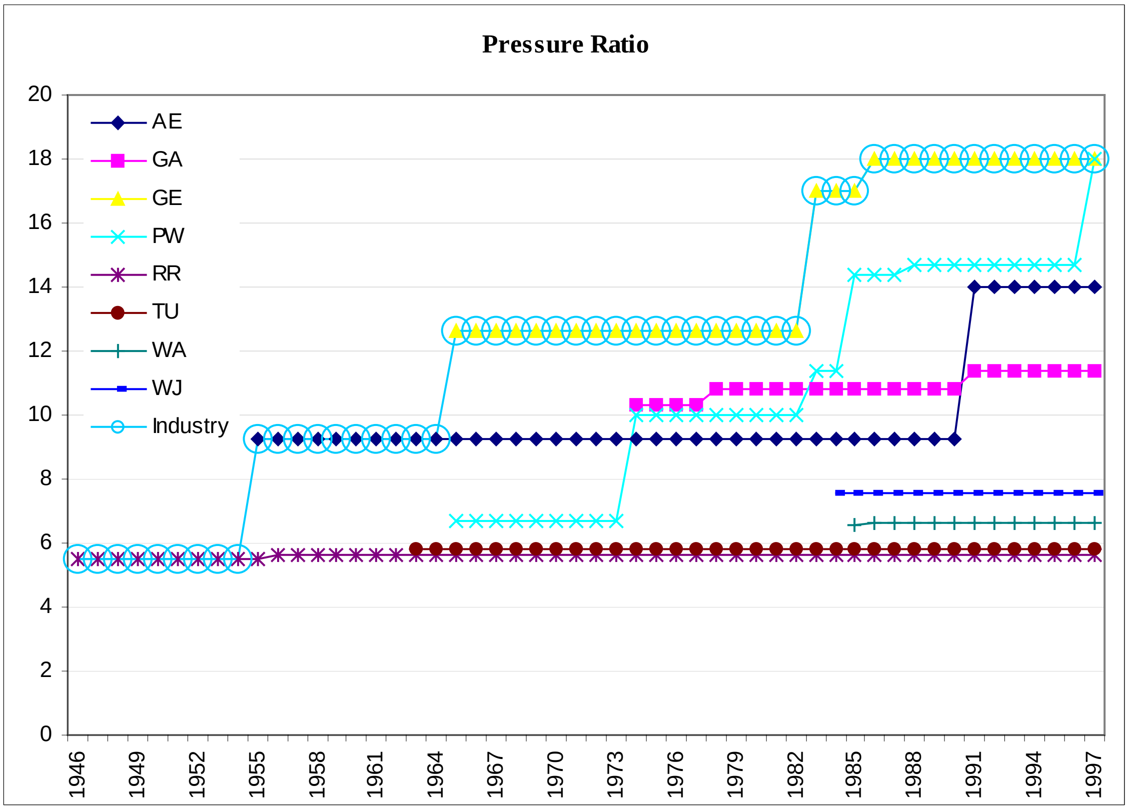
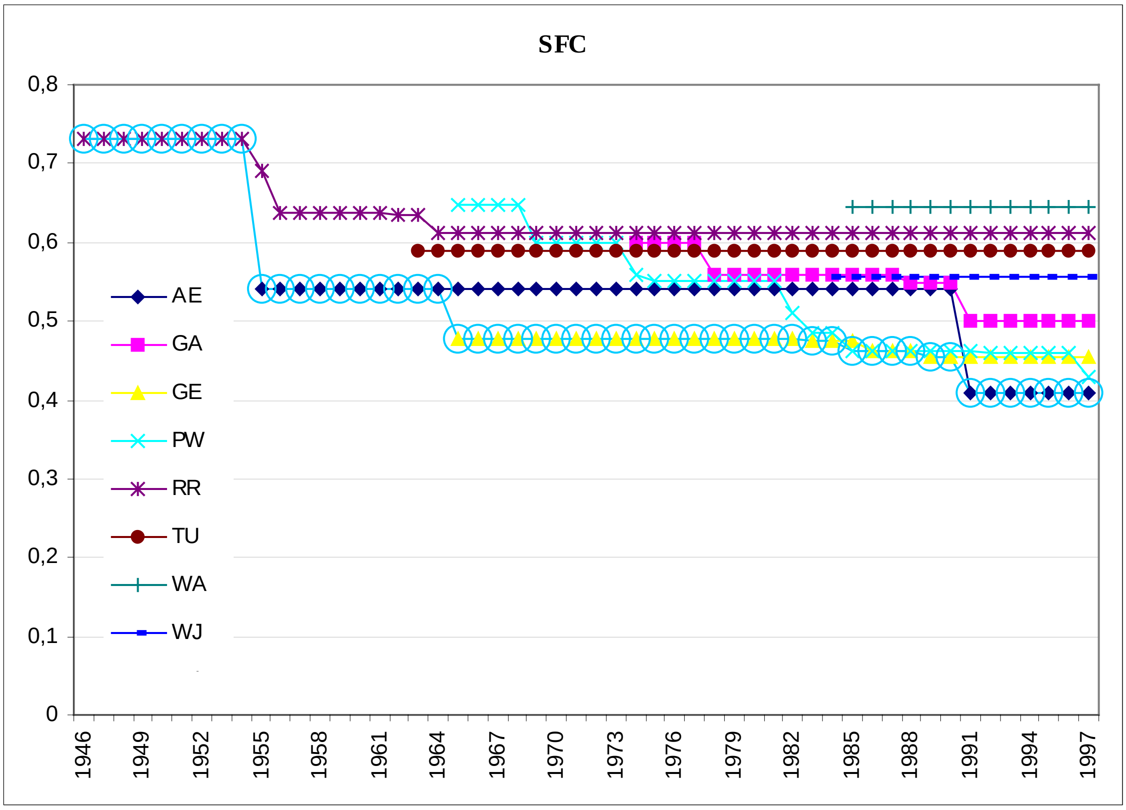


Figure 7b. Technical frontier of industry and firms - SFC



At the cluster level the pattern is even more clear. In cluster 1 the first mover Rolls Royce, single player at the birth of the industry, loses the technological leadership in SFC with the entry of the second mover Allison. In 1965 General Electric enters the industry advancing the technological frontier and a further advance occurs in the 1990s with the introduction of a new engine by Allison. For the pressure ratio the pattern is similar, except for the presence of T values greater than 1 in the 1990s, due to the innovative entry of Pratt & Whitney in the cluster. It is worth noting that once an innovation occurs, the distance from the frontier of the other actors increases and it is not observed a subsequent process of coming up to the frontier, that is companies maintains their technological output, enlarging the gap with the technological leader.

In cluster 2 the first movers Pratt & Whitney and Turbomeca are respectively ont he frontier of PR and SFC. In SFC further technological advances are introduced by Pratt & Whitney and by general Electric until the 1980s. In pressure ratio the pattern is similar, except for the innovative entry of Garrett in the 1970s. The last decade has not been characterised by further innovations, but by stable parallel positions of firms.

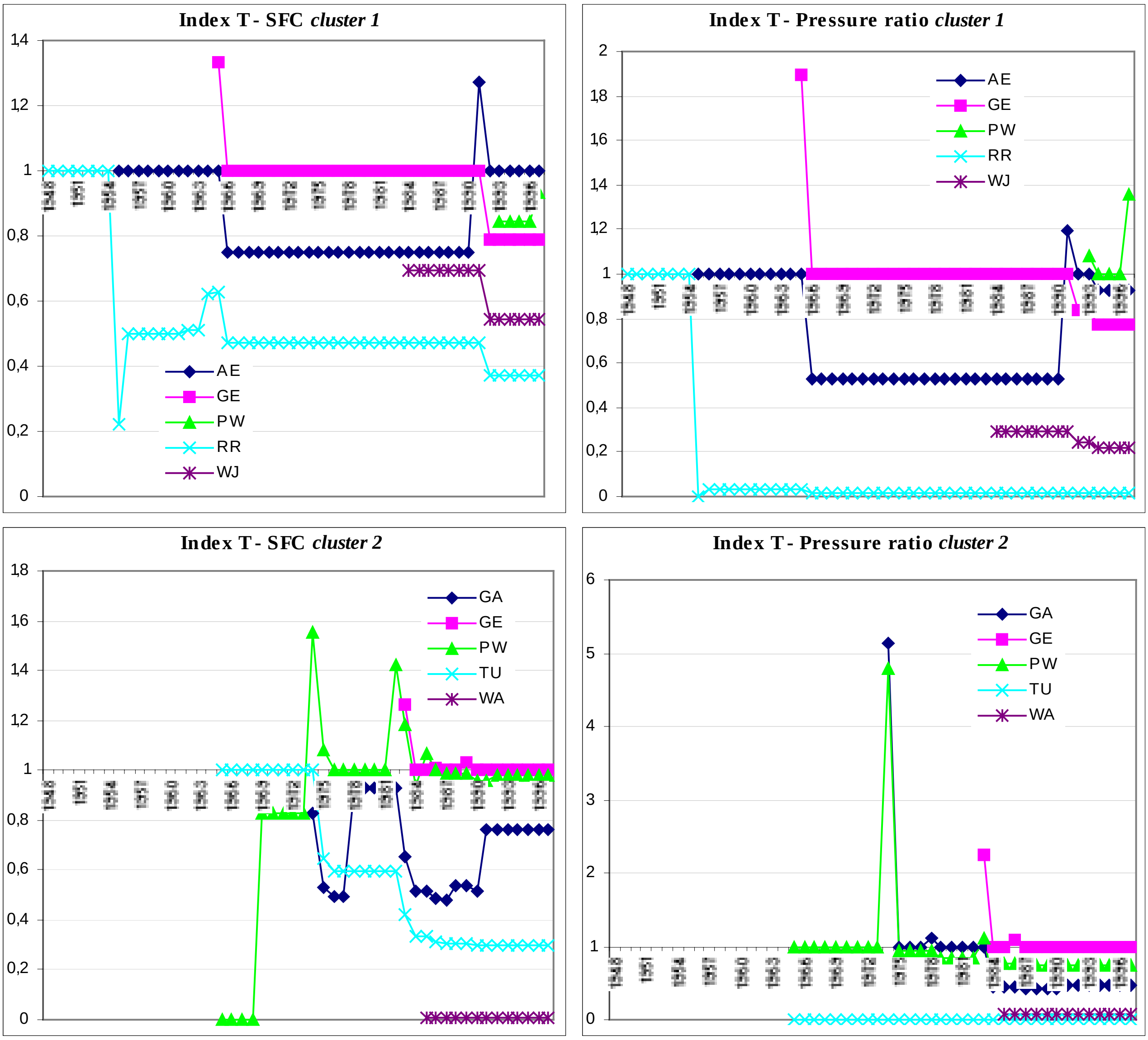
In both clusters we may observe that innovations are isolated and does not seem to influence technological innovation of other companies. Moreover, there is not a single technological leader over all the history, but technological competition is not very intense as, once the technological leader is replaced, actors do not imitate the innovator trying to approach the frontier.

The structure of vertical relations suggests that technological learning occurs in single, one-to-one relations. The existence of a number of partitions in the network, and within of one-to-one relations within partitions, favour the development of separated technological trajectories not in competition among them. For suppliers with a few relations, the opportunities of learning from heterogeneity are limited. Moreover the potential for spillovers almost does not exist, as customers in single sourcing do not have the opportunities for developing “experienced” specification capabilities and cannot act as bridges for the transfer of knowledge across suppliers. Even when customers are in dual sourcing theirircraft programs are in single sourcing and again the opportunities for spillovers are reduced.

Finally, single sourcing does not generate strong incentives to technological innovation for suppliers, as the intensity of competition is lower.

For suppliers having multiple relations, the opportunities of learning from heterogeneity are more pronounced, although learning is fragmented in separated relations with customers in single sourcing.

Figure 8. Index T – cluster 1, cluster 2



In summary, the empirical analysis detailed at the level of single technical parameters seems to support the hypothesis of different intensity of technological competition in hierarchical and non hierarchical networks. In hierarchical networks competition leads to lack of a single leader and to an oligopoly shared among a number of large players. In partitioned networks there is also lack of a single technological leader but the intensity of competition is much lower. While in the jet independent trajectories are observed only for actors at the periphery of the network, such as Allison and Textron, in the turboprop this happens for many companies, even having multiple relations and larger shares of the market such as Rolls Royce.

6. Conclusions and further research

This paper represents an extension of previous research on the relation between network structure and industrial dynamics in vertically-related sectors (Bonaccorsi and Giuri, 2001a,b). The analysis of the processes of technological learning and of the technological positions of actors will provide the basis for micro-foundations of models of interactions among heterogeneous vertically-related actors, and for further specifying the role of demand in the dynamics of industries and technologies.

The paper analyses quantitatively the micro-mechanisms of interactions between suppliers and users and the technological competition among suppliers by focusing on direct measures of output of the technological activity. In this work technological characteristics have been observed separately, with the objective of understanding at a micro-level the possible different directions of innovation pursued by different suppliers. Further research will aim at identifying the weights of each parameters for their aggregation and at estimating a multiparameter technological frontier, linking through specified functional forms technical and service characteristics of products. This is the object of an ongoing research, carried out with the help of aeronautical engineers and technical experts and managers of buyer companies

In this work we develop the empirical analysis of the jet aero-engine industry, which is characterised by the emergence of a hierarchical structure of the network of vertical relations, and of the turboprop industry, characterised by the presence of partitioned network with single and sparse relations. The empirical analysis shows in details the differences in the innovating behaviour and in the intensity of technological competition in the core and at the periphery of the network, and for couples of vertically-related actors. Further research will analyse the relation between technological competition and market performance.

Appendix 1. Data and descriptive statistics of technical parameters and clusters

Table A1. Descriptive statistics of technical and service characteristics

	n	Min	Max	Mean	Std. Dev.	Skewness	Std error Skewness	Kurtosis	Std error Kurtosis
JET									
AIR FLOW lb/sec	114	191.40	3214.20	998.07	683.66	0.724	0.226	0.131	0.449
LENGTH inch	114	56.81	204.02	128.85	27.043	0.310	0.226	0.310	0.449
DIAMETER inch	114	35.79	134.02	70.13	24.78	0.259	0.226	-1.184	0.449
WEIGHT-DRY lb	114	1282.60	16629.80	6320.60	3402.15	0.707	0.226	-0.017	0.449
THRUST T-O lb	114	6975.00	95175.00	34980.65	22571.55	0.777	0.226	-0.301	0.449
BPR	114	0.30	8.40	3.96	2.11	-0.534	0.226	-1.166	0.449
OPR	114	9.40	40.00	24.54	7.85	-0.083	0.226	-1.058	0.449
SFC T-O lb/hr/lb	114	0.32	0.90	0.43	0.13	1.522	0.226	1.595	0.449
TURBOPROP									
LENGTH inch	76	42.99	145.20	87.75	18.3951	-0.026	0.276	2.036	0.545
WIDTH inch	76	19.02	45.31	30.63	7.3485	0.010	0.276	-1.106	0.545
WEIGHT-DRY lb	76	286.00	1753.40	980.20	362.92	-0.255	0.276	-.648	0.545
POWER T-O ehp	76	523.62	6185.69	2049.47	1043.02	1.918	0.276	5.487	0.545
PRESSURE RATIO	76	5.50	18.00	9.87	4.02	0.399	0.276	-1.048	0.545
SFC T-O lb/h/ehp	76	0.41	0.73	0.56	0.08	0.153	0.276	-1.327	0.545

Table A2. Descriptive statistics of service characteristics per cluster

	Parameter	Min	Max	Mean	Std. Dev.	n
JET						
Cluster 1	BPR	0.3	6.6	3.12	2.34	67
	OPR	9.4	33.9	20.68	7.18	67
	SFC	0.32	0.90	0.49	0.15	67
Cluster 2	BPR	5	8.4	5.78	0.93	15
	OPR	31.11	40	35.05	3.42	15
	SFC	0.32	0.39	0.35	0.025	15
Cluster 3	BPR	4.1	6	4.88	0.50	32
	OPR	21	35	27.69	3.76	32
	SFC	0.33	0.39	0.36	0.01	32
TURBOPROP						
Cluster 1	Pressure ratio	5.5	18	7.75	3.73	37
	SFC	0.41	0.73	0.60	0.09	37
Cluster 2	Pressure ratio	5.83	18	11.87	3.20	39
	SFC	0.45	0.65	0.52	0.06	39

Table A3. Distribution of products in clusters - JET

Firm	Product	Cluster	Firm	Product	Cluster
AE	3007A	1	RR	SPEY 511	1
CI	CFM56-2	1	RR	SPEY 512	1
CI	CFM56-2C1	1	RR	SPEY 555-15	1
CI	CFM56-3B	1	RR	SPEY 555-15H	1
CI	CFM56-3C	1	RR	TAY 620-15	1
CI	CFM56-5A	1	RR	TAY 650-15	1
CI	CFM56-5A1	1	RR	TAY 651-54	1
CI	CFM56-5A3	1	TX	ALF502-R5	1
CI	CFM56-5B	1	TX	ALF507-1F	1
CI	CFM56-5B1	1	TX	ALF507-1H	1
CI	CFM56-5B2	1	GE	90-92B	2
CI	CFM56-5B3	1	GE	CF6-80C2	2
CI	CFM56-5B4	1	GE	CF6-80E1	2
CI	CFM56-5C2	1	PW	4074	2
CI	CFM56-5C3	1	PW	4077	2
CI	CFM56-5C4	1	PW	4090	2
CI	CFM56-7B	1	PW	4164	2
GE	CF34-3A1	1	PW	4168	2
GE	CF34-3B1	1	PW	4360	2
IA	V2500	1	RR	Trent 768	2
IA	V2522	1	RR	Trent 772	2
IA	V2525	1	RR	Trent 875	2
IA	V2527	1	RR	Trent 877	2
IA	V2528	1	RR	Trent 884	2
IA	V2530-A5	1	RR	Trent 890	2
IA	V2533-A5	1	GE	CF6-45A2	3
PW	JT3C	1	GE	CF6-50C	3
PW	JT3C-7	1	GE	CF6-50C2	3
PW	JT3D-3B	1	GE	CF6-50E2	3
PW	JT3D-3C	1	GE	CF6-6D	3
PW	JT3D-3D	1	GE	CF6-80A	3
PW	JT3D-7	1	GE	CF6-80A2	3
PW	JT4A	1	PW	2037	3
PW	JT8D	1	PW	2040	3
PW	JT8D-11	1	PW	4056	3
PW	JT8D-15	1	PW	4060	3
PW	JT8D-15A	1	PW	4152	3
PW	JT8D-17	1	PW	4156	3
PW	JT8D-17A	1	PW	4158	3
PW	JT8D-17R	1	PW	4460	3
PW	JT8D-217	1	PW	JT9D-3A	3
PW	JT8D-217A	1	PW	JT9D-59A	3
PW	JT8D-217C	1	PW	JT9D-7	3
PW	JT8D-219	1	PW	JT9D-7A	3
PW	JT8D-7	1	PW	JT9D-7F	3
PW	JT8D-7A	1	PW	JT9D-7J	3
PW	JT8D-7B	1	PW	JT9D-7Q	3
PW	JT8D-9	1	PW	JT9D-7R4	3
PW	JT8D-9A	1	PW	JT9D-7R4E	3
RR	AVON 527	1	RR	RB211-22B	3
RR	AVON 531B	1	RR	RB211-524B	3
RR	AVON 533R	1	RR	RB211-524C	3
RR	CONWAY 508	1	RR	RB211-524D	3
RR	CONWAY 509	1	RR	RB211-524G	3
RR	M45H	1	RR	RB211-524H	3
RR	SPEY 1	1	RR	RB211-535C	3
RR	SPEY 506	1	RR	RB211-535E	3

Table A4. Distribution of products in clusters – TURBOPROP

Firm	Product	Cluster	Firm	Product	Cluster
AE	2100	1	GA	TPE331-10UG	2
AE	2100C	1	GA	TPE331-12UAR	2
AE	501-D13	1	GA	TPE331-14	2
AE	501-DB	1	GA	TPE331-14HR	2
GE	CT64-820-1	1	GA	TPE331-5	2
GE	CT64-820-4	1	GE	CT7-5A2	2
PW	127B	1	GE	CT7-7A	2
PW	127D	1	GE	CT7-9B	2
PW	127F	1	GE	CT7-9C	2
PW	150	1	GE	CT7-9D	2
RR	506	1	PW	118	2
RR	511	1	PW	119	2
RR	512	1	PW	119C	2
RR	514	1	PW	120	2
RR	514-7	1	PW	120A	2
RR	514-7E	1	PW	121	2
RR	525	1	PW	121A	2
RR	525F	1	PW	123	2
RR	528-7E	1	PW	123B	2
RR	529-7E	1	PW	123C	2
RR	532-7	1	PW	123D	2
RR	532-7L	1	PW	124B	2
RR	532-7N	1	PW	125B	2
RR	532-7R	1	PW	126	2
RR	532-9	1	PW	127	2
RR	534-2	1	PW	PT6A-20	2
RR	535-7R	1	PW	PT6A-27	2
RR	536	1	PW	PT6A-45	2
RR	536-2	1	PW	PT6A-45R	2
RR	536-7	1	PW	PT6A-50	2
RR	536-7P	1	PW	PT6A-65A	2
RR	536-7R	1	PW	PT6A-65B	2
RR	542-10	1	PW	PT6A-65R	2
RR	542-10B	1	PW	PT6A-67D	2
RR	542-10K	1	PW	PT6A-67R	2
RR	542-4	1	TU	BASTANVIC	2
WJ	5A-1	1	WA	M-601D	2
GA	TPE331-10R	2	WA	M-601E	2

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