Laboratory of Economics and Management
Sant'Anna School of Advanced Studies

Via Carducci, 40 - I-56127 PISA (Italy)
Tel. +39-050-883-341 Fax +39-050-883-344
Email: lem@sssup.it Web Page: http://lem.sssup.it

LEM
Working Paper Series

Increasing returns and network structure in the evolutionary dynamics of industries

*Andrea Bonaccorsi**
and
*Paola Giuri**

* *Sant'Anna School of Advanced Studies, Pisa, Italy*

1999/12 **October 2000**

INCREASING RETURNS AND NETWORK STRUCTURE IN THE EVOLUTIONARY DYNAMICS OF INDUSTRIES♣.

Andrea Bonaccorsi, Paola Giuri

Sant'Anna School of Advanced Studies, Pisa, Italy

forthcoming in P. Saviotti (ed.), *Applied Evolutionary Economics: New Empirical Methods and Simulation Techniques,* Cheltenham: Edward Elgar, 2001

Abstract

The paper explores the idea that properties at the level of firms coevolve with more aggregate properties at the level of market institutions in the dynamics of industries. We propose that the *structure of network of vertical relations limits the effect of increasing returns* at the firm level. The paper develops a set of empirical measures and discusses a detailed case study of the commercial jet engine industry. The analysis of the structural dynamics of the network of vertical relations between engine suppliers and airframe manufacturers during the history of the industry (1958-1997) explains a final configuration of the industry marked by the coexistence of increasing returns to investments in R&D and marketing activities, with an intense competition among a few large incumbents, a low level of concentration and a strong instability of market shares. The emergence of a hierarchical network with a core and a periphery leads to equalisation of technical and market opportunities within the core and prevents incumbents to exit the industry.

Key words: increasing returns; concentration; market shares; aircraft-engine industry; vertical relations; network.

* Sant'Anna School of Advanced Studies, via Carducci, 40, I-56127 Pisa, Italy.
Phone: +39.50.883323/359, fax: +39.050.883344, e-mail: bonaccorsi@sssup.it, giuri@sssup.it

♣ Comments by participants to the EMAEE Workshop in Grenoble were extremely useful. The financial support of the Italian Ministry of Research (MURST 40% - "Industrial dynamics and interfirm relations") is gratefully acknowledged.

1. Introduction

The role of increasing returns in the explanation of the dynamics of economic systems, and of industries in particular, has recently received new attention.

Endogenous growth theory has pointed out the role of increasing returns arising from the repeated use of productive knowledge at the level of countries and regional systems (Romer, 1986, 1990, 1991). New trade theory stresses the importance of increasing returns to scale and imperfect competition in explaining international trade (Helpman and Krugman, 1985; Krugman, 1990, 1994). Business history has offered a rich repertory of cases in which companies, that were able to pursuit economies of scale and scope and invest in technology, organisation and marketing, reached a position of dominance in the industry (Chandler, 1990). Theories of industry life cycle are based on the assumption that, while product innovation does not favour per se large firms, innovation in manufacturing processes and process R&D is subject to increasing returns, favouring large incumbents over smaller or newer firms (Klepper, 1996). In the diffusion of competing technologies, a great deal of attention has been devoted to increasing returns to adoption, or positive feedbacks on the demand side, to explain the emergence of technological monopolies (David, 1985; Katz and Shapiro, 1985; Arthur, 1989; Bassanini and Dosi, 1998).

While this renewed interest must be considered positively, it also creates delicate theoretical problems to evolutionary economics. In fact, in evolutionary economics properties at the level of individual agents (e.g. cost structures of firms) are not sufficient to explain the observed dynamics at the level of the economic system. Properties of dynamics such as non-stationarity and non-ergodicity must be specified in order to derive results at the higher level. These properties should reflect the role of variety generation, selection and retention as drivers of economic change. Therefore theories that derive higher level results from just an assumption of increasing returns pose a challenge to evolutionary economics.

For example, as witnessed by the recent debate on the economics of QWERTY (David, 1997) there is a sharp distinction between the notion of path-dependency and market failure. Critics of evolutionary economics point out that increasing returns is all that is needed for explaining the dynamics of economic systems, with possibly path-dependency as a special case of limited empirical relevance, which is responsible for market failures (Liebowitz and Margolis, 1995). Paul David (1997) argues that "path dependency is neither a necessary nor a sufficient condition for market failure". Path dependence, that is a dynamic property of sequential stochastic processes, implies that historical events shape the dynamics of economic systems, but path dependence is not necessarily related to the emergence of sub-optimal outcomes.

To evolutionary economics, increasing returns are but one element of the picture. The engine of economic growth, and of industrial dynamics, is thought to be located at the level of properties of population, not only of properties of individual agents. As an example, Bassanini and Dosi (1998) demonstrate that unbounded increasing returns to adoption are neither a necessary nor a sufficient conditions for the emergence of technological monopolies, but the relative impact of increasing returns and heterogeneity of customer preferences determines technological monopoly or market sharing.

It can be argued that while differences in initial conditions, as represented for example by variety of agents characteristics, become magnified by positive feedback and determine the final outcome of economic systems, more aggregate coordination mechanisms may influence the dynamics of the system preventing the effects of increasing returns to take place. Metcalfe (1999) maintains that "aggregate growth is an emergent property built upon the coordination of diverse micro behaviours, and it is through the interaction of the micro behaviours that the dynamics of change occurs". Variety of agents characteristics is not the only determinant of firms' competition, but market institutions coordinate the competitive process. The decisions of individual firms are embedded in an institutional context that shapes the returns to their investment decisions. Nelson (1994; 1999) suggests that firms' competitive advantage resides not only within the firm, but also at the level of the nation or of the networks of key actors (suppliers, customers or other supporting institutions). Mowery and Nelson (1999) collected several case histories in which different institutional factors influence industry evolution.

The purpose of this paper is to develop an argument for the impossibility of deriving higher level results in the *long run dynamics of industries* from the assumption of increasing returns at the level of individual agents. We discuss a detailed case study of an industry - the commercial jet engine industry - in which technological evolution brought about very strong conditions of increasing returns, but the shakeout did not take place. We produce evidence of a case which falsifies the proposition that increasing returns are a necessary and sufficient condition for concentration of the industry. What is the explanation of this observed anomaly?

We argue that the effect of increasing returns on industrial dynamics are filtered through the structure of vertical relations. At the level of population, technology conditions giving origin to increasing returns and market institutions coevolve and jointly shape the dynamics of competition. We introduce an institutional factor which refers to the *vertical market structure*. In oligopsonistic industries the structure of vertical relations is a major determinant of the industrial dynamics in the supplier industry. Although positive feedback mechanisms at the firm level may well exist, the final outcome of competition may be filtered by the structure of demand relations.

The paper develops an empirical analysis of the structural dynamics of the network of vertical relations between engine suppliers and airframe manufacturers during the history of the commercial jet engine industry (1958-1997). The changing structure of the network of vertical relations between suppliers and buyers explains a final configuration of the industry marked by the coexistence of increasing returns to investments in R&D and marketing activities, with an intense competition among a few large incumbents, a low level of concentration and a strong instability of market shares. Interestingly, this empirical evidence is not consistent with the explanatory results of theories of industry life cycle, also confirmed by simulations models (Mazzucato, 1998).

We propose that *the effects of increasing returns are limited by the structure of the network*. The emergence of a hierarchical network with a core and a periphery leads to equalisation of technical and market opportunities within the core and prevents incumbents to exit the industry. Instead of an increasing level of concentration and market stability in the final stages of industry evolution, we observe strong market share instability and turbulence of the players' positions.

The paper is organised as follows. Section 2 develops a discussion on the sources of increasing returns in the dynamics of industries. It reviews the factors leading to changing conditions of increasing returns on the supply side and on the demand side of the industry and analyse their effects on the final outcome of the industry. In some cases, lack of increasing returns conditions leads to a non shakeout pattern of industry evolution. In other cases the emergence of increasing returns may be limited by market institutions, precisely by the vertical structure of the industry.

Section 3 presents data and measures used for the empirical analysis. We use a proprietary database, built upon several sources of data, whose originality lies in the presence of data on each supplier-buyer relation, which are used to calculate different network measures. Industry measures on concentration and market share instability and statistics on introductions of products and versions are also described.

Section 4 exposes the evolution of the commercial jet engine industry by focusing on factors leading to increasing returns, i.e. product innovations and marketing relations, and on the dynamics of the network of vertical relations. The structural dynamics of the industry, as described by concentration, market share instability and change in the rank of suppliers, is discussed in light of the dynamics of the network. Section 5 discusses how the network prevents the effects of increasing returns to take place and section 6 concludes.

2. Increasing returns in the dynamics of industries

The role of increasing returns in the dynamics of industries has been formalised in theories of industry life cycle (Klepper, 1996). In the presence of increasing returns to process R&D and manufacturing, they predict a shakeout pattern of industry evolution. Results of simulation models based on replicator dynamics show that the presence of dynamic economies of scale leads to increasing concentration and stability of market shares during the later stages of industry evolution, while the early stages, mainly characterised by negative feedback, exhibit market share instability (Mazzucato, 1998).

We call attention on three facts: first, conditions for increasing returns may exist also in other areas of firms' activities, i.e. product R&D and marketing. In some cases, however, specific features of demand and technology may not lead to the emergence of increasing returns. Second, violation of increasing return conditions may explain departures from ILC. Third, even in the presence of increasing return conditions, the vertical structure of the industry may prevent the effects of increasing returns to take place.

2.1 Sources of increasing returns

The discussion in industry life cycle models is carried out mainly on the emergence of dynamic increasing returns to scale in process R&D and manufacturing activities. As Chandler (1990) emphasises, positive feedback may also emerge in other areas of productive activities, such as organisation and marketing. Furthermore, increasing returns may emerge both on the supply side and on the demand side of the market. David (1997) observes that "in a dynamic process, positive feedbacks will be generated by the dominance of indivisibilities and strong technical complementarities on the supply side of markets; and/or interdependence of customer preferences operating on the demand side". In their study of the shakeout of the automobile tire industry, Klepper and Simons (1999) introduce the role of technology and of factors such as localisation and distribution networks as additional sources of positive feedback that favour large incumbents.

In this section we explore significant factors leading to changing conditions of increasing returns to R&D, manufacturing and marketing activities. We explore how the effects of characteristics of demand such as discontinuity, heterogeneity and relational investments, or the presence of network externalities, can prevent the emergence of increasing returns.

Increasing returns to manufacturing

With respect to manufacturing, the effects of increasing production on the rate of cost reduction have often been emphasised. Klepper (1996) made it clear that the applicability of industry life cycle models is limited to products with rich opportunities for both product and process innovation, and that the "joint nature of product and process innovation drives the product life cycle". Consequently, industries characterised by homogeneous goods subject only to process innovations (e.g. synthetic fibres and plastic) or industries with opportunities mainly for product innovations (e.g. heavy electrical equipment which is typically produced in small batches) do not follow this pattern.

ILC models are based on the assumption that firms make *separate decisions* on investments in product and process R&D. In particular, at the birth of the industry firms invest only in product innovations. Following the shakeout, incumbents' investments in process technology increase and investments in product design decrease. This suggests a slowdown in the rate of technological progress, which is now focused on process improvements directed at cost reductions (Agarwal, 1998). This picture depicts especially the evolution of mass production industries, in which the emergence of product standardisation or of a dominant design reduces uncertainty over physical parameters of product design and increases the profitability of process innovations.

On the contrary, in many other industries products are realised in small batches and/or in single units, with large variations of design parameters across products at the same date and over time, so that large economies of scale in manufacturing and benefits from standardisation are largely lost. Product and process technology cannot be easily separated. This situation applies to industries such as large equipment and capital goods, telecommunication systems, energy infrastructure, construction, railway and other transport systems. In these industries companies try to minimise variations in the models introduced and maximise the total output but cannot rely on large volumes in order to plan the production activity over a sufficiently long horizon.

When *products are highly customised*, process technologies are mainly of general purpose type, and skilled-labour-intensive. Specific tools for productive processes are designed jointly with new products. In most cases it is almost impossible to increase the throughput rate of the production process. In sum, process technology may experience increasing returns to scale much later in the industry life cycle than is the case in mass-production industries. In sum, there are good reasons to expect that in some industries increasing returns to manufacturing are not so important.

In the case of *demand discontinuity* the linkage between increasing returns in manufacturing and industrial dynamics is not clear. In life cycle models once a dominant design emerges, incumbents plan the expansion of production capacity, invest into process technologies, appropriate process innovation, produce at low cost and force less efficient competitors to exit the industry. This sequence may be precluded in some industries so that, even though increasing returns are important, the shakeout does not take place. Under conditions of demand discontinuity, incumbents may have no incentive to plan large capacity expansion and to drive competitors out of the industry, for two reasons.

The first is that capacity expansion may be too risky if it is not followed by exit of competitors. In fact, discontinuity implies that the aggregate demand dynamics are irregular and badly behaved, so that manufacturers may be good in long-term forecasting of quantities, but fail to identify the time-path of orders. If production costs are sensitive to the rate of production, this may be extremely expensive. Under these conditions, the dynamics of market demand is likely to generate cobweb phenomena, with associated peaks of excess demand and large backlogs in orders. Manufacturers are slow in adjusting production capacity to increase in demand. Discontinuity of demand also influences the choice of techniques and discourages investments in capital intensive methods of production[1].

The second reason is that it is not always possible to force competitors out of the industry, making sure they will not enter at future dates. In production-to-order industries, particularly in project-based industries, large contracts are awarded to suppliers, generating streams of orders during long periods of time. Windows of opportunity are open at discrete stages, normally through long and severe bidding procedures during which cut-throat competition takes place. Gaining the contract in the bidding stage is of paramount importance for suppliers, since there may be no market alternative in the short term. If, in addition, market demand is heavily concentrated (which is common in these industries), the total number of windows of opportunity may be so small that each of them influences the probability of survival of individual firms. A firm cannot survive by losing several bids in sequence[2].

Finally, discontinuity of demand prevents any single producer from monopolising the industry. Customers would never support a monopolistic industry, which might expose them to scarcity and/or very long delays in delivery. The active support of alternative sources of supply is a feature of demand regime in these industries.

In all these cases the critical factors are the characteristics of demand and the structure of vertical market relations. Increasing returns lead to increasing industry concentration if and only if customers are willing to support a more concentrated supply industry, by switching from small suppliers to large ones. This is not the case in most situations.

In sum: a) there are industries in which increasing returns to manufacturing are not important; b) there are industries in which, even though they are important, their impact is limited by the vertical market relations.

---

[1] For example, anecdotical evidence suggests that, in the aircraft industry, plants dedicated to military production are more capital intensive than plants for civil production. The reason is that military programmes specify in advance the rate of delivery over the entire life span of production, so that the cost of more capital-intensive techniques can be recovered over given quantities, while in the civil sector rates of production fluctuate wildly and cannot be smoothed efficiently.

[2] Peck and Scherer (1962) provide a detailed description of the stage of source selection in the weapon acquisition process as a competition among multiple suppliers to gain program participation. Suppliers' competition is much more frequent for the first contract award, while for subsequent orders contract awards are usually negotiated non-competitively with a single firm, that is, the winner at the bidding stage. Selection is especially based on technological considerations - quality, time of availability and costs. However, these industries exhibit *both* fierce price competition and non-price competition based on product differentiation and technological supremacy. Firms have the tendency to quote a price below average costs, trying to recover the profitability during the life cycle of the contract (for example, through engineering modifications, additional works, or maintenance and spare parts). This means that new entrants or followers have the incentive to make dumping against incumbents. Winner's curse is common in these industries, so that eliminating competitors may be extremely expensive for incumbents.

Increasing returns to R&D

Increasing returns to R&D may originate from indivisibility and complementarity effects (at both the human capital formation and the technical infrastructure level) or from economies of scope in the application of generic level technology (mainly of fundamental type) to many areas of business. Depending on the importance of R&D on the cost structure, increasing returns in this area may more than compensate the effects of cost conditions in manufacturing. For example, in the jet aircraft industry the indivisibility effects in new product development and economies of scope across products and families are so important that the industry underwent a shakeout, even though economies of scale in manufacturing are not very relevant.

In other cases, on the other hand, there may be specific conditions that prevent the emergence of increasing returns to R&D. One is *heterogeneity* in customer preferences over technical features of products. In some industries customers exhibit differentiated technical requirements, based on specific characteristics of their technical systems. In oligopsonistic industries even individual customers may have a decisive impact on suppliers' technical choices. This means that exploration does not take place over the entire space of design parameters, but rather in directions dictated by the interaction with customers. Trial and error search in the initial stage of ILC is ruled out, while focused search is predominant. The existence of increasing returns in R&D is therefore a matter of empirical appreciation at very fine level. Even technologies that appear similar may reveal deeply different technological micro-regimes, with associated returns conditions to the investment in R&D.

Increasing returns to marketing

With respect to marketing, much attention has been devoted to the presence of interdependences of customer preferences and on the emergence of increasing returns to adoption. Arthur (1994) observes that "not only the costs of producing high technology products fall as a company makes more of them, but the benefits of using them increase.... when one brand gains a significant market share, people have a strong incentive to buy more of the same product so as to be able to exchange information with those using it already". Incentives to buy the products increase also in the presence of networks for spare parts or repair services (Farrell and Saloner, 1985). Investments in post production activities can be an important source of positive feedbacks on the demand side if compatibility is necessary for users to exchange post sales services or information. Positive feedbacks on the demand side also derive from transmission of information by users who learn by repeatedly using the product of the same supplier (Rosenberg, 1982).

On the contrary, features of demand such as *customer heterogeneity* and the relevance of *relational investments* point to lack of significant economies of scale and scope in dealing with customers.

ILC models implicitly assume a continuous flow of demand on the part of a large group of homogeneous customers. More precisely, customers may exhibit differentiated preferences over bundles of product attributes, but these preferences are distributed over the entire region explored by companies. Once a dominant design appears in the market, previous design configurations become dominated over most of the distribution of preferences. Customers migrate to the dominant design, while dominated alternatives survive in market niches. In this process, the preferences of individual customers do not interact heavily with technical development. While this is mainly true for most consumer industries and for some intermediate industries, it is far from being general. Windrum and Birchenall (1998) recently showed that the existence of heterogeneous users may lead to several alternative designs within a market niche.

While heterogeneity heavily influences both R&D and manufacturing costs, it also implies that firms must make *fixed* investment to *each* customer relation. Market demand cannot be addressed without making heavy investments in *relational* activities. Heterogeneity of customers may take place across segments, or even across single buyers. In these cases cross-selling is not possible and marketing synergies across segments are lost. Highly idiosyncratic customer needs require careful adaptation of products. As an example, aircraft manufacturers have to offer many cosmetic modifications to the aircraft to meet the extremely customised airline requirements. Warwick (1998) reports that over five years of all Boeing models “more than 14,000 changes were processed for customer airlines. Of those changes, 72% were for single customers; i.e. 10,000 changes were produced based on single requests from the airlines, while only 4,000 were shared by two or more customers”.

Users influence marketing, design, production and post-production (maintenance, upgrading) activities of suppliers to a considerable extent. Supplier-user relations involve reciprocal investments in the relationship, strong technical cooperation during the design phase and risk sharing on the part of suppliers, explaining the existence of tight and stable relations over time. Close interactions among users and producers take place during the design activity because of the need for continuous feedback. The stability of these relational linkages is also the result of sunk investments into relationship-specific procedures and managerial routines, dedicated technologies and human capital, logistic infrastructure or relational trust.

2.2 Lack of increasing returns and non shakeout

While shakeout patterns have been empirically detected in many industries, non-shakeout patterns, characterising a large portion of modern manufacturing, have received less attention. Recently, research has been devoted to investigate the factors leading to non shakeout patterns.

Klepper (1997) explored alternative paths to ILC in three groups of industries which did not experience a shakeout according to the Gort and Klepper (1982) study. Commenting on Klepper’s classification, Bonaccorsi and Giuri (2000a) argued that departures from the ILC pattern fall into two broad categories: violations of appropriability conditions and violations of increasing returns conditions. The former apply to industries in which, mainly due to *processes of division of labour*, the appropriability of benefits from investments in product and process R&D is reduced, so that the bases for sustainable advantage of incumbents are eroded. This categories corresponds to the first and the second case in Klepper's analysis (Klepper, 1997). The latter applies to industries in which there is *lack of increasing returns to R&D, manufacturing or marketing*, due to characteristics of technology or market demand. More precisely, the evolution of technology and demand does not bring about the emergence of significant economies of scale and scope in some of the stages of productive activities. The third case identified by Klepper (1997) falls into this category, with reference to the pattern discussed by Phillips et al. (1994) in the business jet industry. However, the explanation of non shakeout is given mainly in terms of demand fragmentation and strongly heterogeneous customer preferences, which prevent the standardisation of products and the emergence of increasing returns to manufacturing. Bonaccorsi and Giuri (2000a) argue that demand factors are not sufficient to produce a non shakeout pattern and that a more comprehensive explanation must take into account and balance accurately cost structures in R&D, manufacturing and marketing activities.

In sum, lack of increasing returns in all stages of productive activities should lead to a non shakeout pattern, as incumbents could not prevent entry and growth of competitors through cost advantages. This occurred in the commercial turboprop engine industry, in which non separability between product and process innovation, absence of economies of scope in R&D and demand segmentation implied lack of increasing returns across all stages. In general, the long term outcome of an industry dynamics depends on the effects of different evolving return conditions.

2.3 Increasing returns and vertical structure of the market

Increasing returns at the firm level are not the only factor explaining the dynamics of industrial competition. We introduce an *institutional* factor which refer to the *vertical structure of the market*. While the presence of increasing returns should lead incumbents to dominate the industry, the structure of market relations at a higher level determines the final outcome of competition.

For example, in intermediate good industries, technological complementarities often exist in the buyer-supplier relation. Vertical relations are thus associated to switching costs for buyers, whose existence favours incumbent suppliers with respect to entrants in the competition for orders by existing customers. Similar observations apply in the case of adoption of single sourcing. Again, incumbents enjoy advantages in gaining subsequent orders of existing customers. On the contrary, shift to multiple sourcing breaks exclusive relations and opens the competition between entrants and incumbents. Although positive feedback mechanisms at the firm level may well exist, the final outcome of competition may be filtered by the structure of demand relations. In oligopsonistic industries the structure of vertical relations has been found a determinant of the competition in the supplier industry (Bonaccorsi and Giuri, 2000b,c).

In this paper we discuss a case - the commercial jet engine industry - in which, while conditions of increasing returns have emerged, the industry did not undergo a shakeout. Instead of an increasing level of concentration and market stability in the final stages of industry evolution, we observe strong market share instability and turbulence of the players' positions. This is very different from the pattern observed in the aircraft industry, which shares the same conditions for increasing returns, and in which concentration increases enormously while the leader maintain its position.

We propose that *the effects of increasing returns are limited by the structure of the network*. The emergence of a hierarchical network with a core and a periphery leads to the equalisation of technical and market opportunities within the core and prevents incumbents to exit the industry.

3. Data and methodology

3.1 Data

We use a proprietary database built upon several sources of data to reconstruct the life of the commercial jet engine industry since its birth. Specifically, we use the *Atlas Aviation* and *Jane's All the World Aircraft* databases, IATA publications and literature on the history and technological development of the aviation industry[3]. The *Atlas Aviation Database* contains all the transactions occurring from 1948 to 1997 between aircraft manufacturers and airline companies (orders) in the market for large commercial aircraft. The data distinguish the engine technology adopted, jet and turboprop, and for each transaction it is possible to identify the engine model integrated into the aircraft ordered. For the purpose of this study, we use data relative to the jet engine.

The empirical analysis is based on descriptive statistics and graphical data analysis on introduction of products, industry instability and network of vertical relations over time. In Bonaccorsi and Giuri (2000d) we identified three different periods based on major entry events: 1958-1966, 1967-1980 and 1981-1997. Each period was marked by changes in technological and market uncertainty and differentiated patterns of network evolution. This 3-period classification also guides the empirical analysis of this paper.

3.2 Industry stability

The industry stability is analysed in terms of mobility of players and of level of industry concentration, instability of market shares and turbulence of players' positions.

[3] Among others, Miller and Sawers, 1968; Phillips, 1971; Klein, 1977; Constant, 1980; Bluestone et al., 1981; Bright, 1981; Mowery and Rosenberg, 1982, 1989; Hayward, 1986, 1994; Vincenti, 1990; Rowe, 1993; Norris and Wagner, 1997; Sutton, 1998.

Industrial concentration

Data on which concentration measures are computed are based on total sales of commercial aircraft manufacturers over the entire period of observation, expressed in physical quantities (orders). To take into consideration sales of aero-engine firms, aircraft orders are multiplied by the number of engines installed in the model, as described in the technical literature. We do not consider the market for spare engines. Market shares are therefore defined in terms of quantities rather than turnover, since there is no such detailed information available at the level of individual aircraft and engine programs.

We compute two concentration measures: the CR(K) and Herfindahl indexes[4]. In the first indicator, K is set at 2, because in heavily concentrated oligopolistic industries such as aero-engines, the sum of the cumulative market share of the first two companies is a good measure of industrial concentration. Also, at the birth of the jet industry, there were no more than two players. The CR2 index allows detecting the transition from a duopolistic to an oligopolistic industry structure.

In oligopolistic industries, the Herfindahl index provides a rough measure of the intensity of the competition among major players. When the number of firms is very small and the industry is composed of a few large players, a low Herfindahl index may indicate the presence of an oligopoly in which market shares are similar among the leaders.

$$CR(K) = \sum_{i=1}^{K} S_i$$

S_i = market share of the company *i*

I = 1,2, ..., E engine manufacturers

$$HERF = \sum_{i=1}^{E} S_i^2$$

Market share instability and turbulence of the players' positions

Market shares instability and rank mobility are measures of the intensity of competition and they may show the movements underlying structural stability that can be indicated by concentration measures. In fact, concentration indexes do not tell anything about the distribution of shares among companies and about the abilities of leading firms to maintain their relative positions (Hymer and Pashigian, 1962; Gort, 1963; Jacoby, 1964; Caves and Porter, 1978; Baldwin, 1995). A measure of the shifts in the relative position of the firms within an industry is also considered an important indicator of the intensity of the competition (Joskow, 1960; Geroski and Toker, 1996). The joint analysis of concentration and mobility measures provides quantitative measures and allows more detailed qualitative judgement about the evolution of the industry and of the intensity of competition.

We calculate the Pashig index of market share instability (Baldwin, 1995) in three periods of the industry life cycle.

$$PASHIG = \frac{\sum_{i=1}^{K} \left| S_{i,t} - S_{i,t-1} \right|}{2}$$

S_i = market share of the company *i*
t = final year of the period
t -1 = first year of the period

The value of the index lies between 0 and 1. The larger the value, the higher is the intensity of competition. We distinguish as to whether market share instability is caused by entrants or by competition among incumbents.

We also analyse the change in the players' position during the three periods of industry evolution. We build transition matrices according to the rank in the three periods, indicating the frequencies of cases in which a firm in a given position at the beginning of the period *z* changes its initial position during the period.

The three square matrices assume the following form:

$\mathbf{T_z}$

	#1	**#2**	**>2**
#1	X_{ij}	...	...
#2	...	...	...
entry	...	...	...

where $X_{ij} = \frac{a_{ij}}{T_z}$

a_{ij} represents the number of years a firm occupying position *i* at the beginning of the period *z* is positioned in *j* during the period.

T_Z is the total number of years of the period *z*, where *z* = 1,2,3 indicates the stage of the industry life cycle. The size of the matrix is determined by the number of incumbents at the beginning of the period + 1, which represents entry.

We can see if the observations are concentrated on the diagonal and analyse their values to assess the degree of rank stability and hence the turbulence in market leaders. Complete rigidity of ranks is indicated by a single diagonal row of 1 from upper left to lower right in the matrix. Observations above the diagonal indicate companies losing positions, observations below the diagonal indicate companies gaining positions. Large values of X_{ij} off the diagonal indicate high turbulence in the players' positions.

3.3 Introduction of new products

We are able to trace the introduction of new engines through the entire history of the industry.

4

Data allow the distinction between new programs and new versions within the same program. We therefore compute the following variable:

– total number of products and introduction of new products in the three different periods, by entrants or incumbents;

3.4 Measures of economies of scale and scope

In order to demonstrate conclusively the existence of increasing returns, one should make detailed cost analysis. Following the engineering approach, Pratten shows that aircraft production is subject to strong economies of scale, with an increase in production costs at half the MES of 20% (European Commission, 1988). It is more difficult to obtain data which allow the distinction between jet and turboprop technology, and data on aircraft engines, particularly in the commercial sector. While in the military sector the very structure of procurement contracts forced defence contractors to make publicly available extremely detailed cost data, some of which have also been the object of published econometric analysis (Alchian, 1963; Marshack et al., 1967; Large et al., 1974, 1976), this does not apply at all to the commercial sector, where detailed data are sensitive.

We therefore must look for indirect measures of economies of scale and scope. In the design and manufacturing of airframe and engine products, the most effective way to exploit economies of scope is to utilise the same basic version as a bottom line for developing a family of products. It is also possible to obtain economies of scale by maximising the commonality of components across versions and planning the utilisation of a larger capacity.

We build a set of indicators at the product level which provide the basis for assuming the presence of increasing returns:

– number of engine versions per engine program;
– number of applications (aircraft programs and aircraft versions) per engine program.

3.5 Network measures

Network indicators are drawn from graph theory and social network analysis and adapted for the analysis of vertically related industries (Scott, 1991; Wassermann and Faust, 1994; Borgatti and Everett, 1997)[5].

The structure of the relations is represented for each year by an interaction matrix A, whose cells represent the binary variable a_{ij} “a relation exists or does not exist”.

The analysis of two-mode networks in the literature is not as much developed as that of one-mode networks and the range of measures available is thus somewhat less sophisticated. For the aims of this research we use modified versions of centrality measures at actor and group level.

---

[5] A part of this section has been developed in Bonaccorsi and Giuri (2000b).

At the single actor level we calculate *degree centrality indexes*. The degree of an actor is defined as the number of lines incident with that node.

$$CD_i^E = \sum_{j=1}^{A} a_{ij}$$

$$CD_j^A = \sum_{i=1}^{E} a_{ij}$$

a_{ij} = relation between the companies *i* and *j*
i= *1,2,....,E* engine manufacturers
j= *1,2,....,A* aircraft manufacturers

CD_i^E and CD_j^A are respectively the degree of aircraft and engine manufacturers. The degree of an aircraft manufacturer, that is the number of its suppliers, represents the sourcing strategy (single or multiple) of aircraft manufacturers.

At group level we calculate a *measure of relational density* and a *centralisation index*. The *density* is a count of the number of ties actually present in a graph, divided by the maximum possible number of ties in a graph of the same size. It provides information about the group relational intensity and the cohesion of a graph.

$$DENSITY = \frac{\sum_{i}^{E}\sum_{j}^{A} a_{ij}}{A * E}$$

We show in the analysis how the value and the change of relational density depends on the *numerator*, which shows the intensity of the relational activity among companies, or on the *denominator*, which includes information about entry and exit of companies for each year of the period.

The second group-level measure is the *centralisation index*, which measures the extent to which a particular network has a highly central actor around which highly peripheral actors collect (Borgatti and Everett, 1997). The index has the property that the larger it is, the more likely it is that a single actor is central, with the remaining actors considerably less central. It measures how variable or heterogeneous the actor centralities are, providing a measure of inequality and a rough approximation of variability of actors' values (Wasserman and Faust, 1994). We use a modification of the standard Freeman degree centralisation index (Freeman, 1979). The index is obtained in two steps. In the first we sum the differences between the degree of the most central actor and the degree of all the others. In the second we normalise by the maximum possible sum of differences.

$$GroupCentralisation = \frac{\sum_{i=1}^{E}(CD_i^{MAX} - CD_i)}{\sum_{i=1}^{E}(CD_i^{*} - CD_i)} = \frac{\sum_{i=1}^{E}(CD_i^{MAX} - CD_i)}{(A-1)(E-1)}$$

CD_i^{MAX} = maximum degree

CD_i^{*} = possible maximum value of degree (theoretical)

At the group level we identify the existence of *cohesive subgroups*, which are subsets of actors among whom there are relatively intense ties. In this analysis the subgroup is composed of all actors having a minimum of 2 relations for at least 5 consecutive years during the period under analysis. Actors which correspond to these criteria (nodal degree and stability of the relation) are selected as members of the core during the entire industry life.

In this way we identify a *core* and a *periphery* of the network. The core is composed of the portion of the network whose members have ties to many others within the subgroup. On the contrary, the periphery is composed of actors with only one relation or with two unstable relations. We calculate relational density and group centralisation at the core level in order to highlight relational dynamics within the core and to identify effects of structural differentiation and hierarchical organisation of the network.

3. The structural evolution of industry and network

3.1 A brief history

From the beginning of the powered aircraft industry until the Second World War, the propeller-piston engine combination was the predominant aircraft propulsion system. The search for alternative forms of propulsion systems was driven by the military need to operate at higher altitude and speed in order to avoid counter-air defence. The successes and failures experienced during the inter-war period while trying to meet these requirements by developing gas turbines did result in the affirmation of two propulsion systems: *turboprop* and *turbojet* (Constant, 1980). After the war the turbojet became the most diffuse power system for military aircraft, but for any application in the commercial market, the jet engine had to become more durable and economical than it was in 1945 (Miller and Sawers, 1968).

A few companies assumed the risk of developing engines for civil applications. Aircraft and engine manufacturers had to cope with a high degree of *technological and market uncertainty*. On the technical side, the introduction of the turbojet had a strong impact on aircraft design. After the war airframes were unsuited for the new performances and functionality that the jet technology could offer. Therefore, a long period of *coevolution of engine and aircraft design* followed, which was subject to fundamental uncertainty concerning the scientific rules underlying the integration of engine and airframe. The resolution of such uncertainty required exceptionally intense experimentation and testing activities. The decision to adopt the new technology depended on the extent to which it could be easily tried, and therefore on the development and availability of specific experimentation and testing facilities and procedures.

On the commercial side, the applicability of jet engines to civil aircraft demanded reductions in operating cost and improvements in safety, durability, reliability and take-off performance. The decisions of airliners to adopt the jet technology was characterised by significant uncertainty about the possibility of the turbojet engines to meet these requirements economically.

Two engine companies entered successfully the industry at the first stage: Rolls Royce and Pratt & Whitney. In 1952 the de Havilland Comet, powered by the Rolls Royce Avon jet engine, entered the market but was plagued by severe metal fatigue problems. In 1958 the modified version Comet IV entered the market, but was a commercial failure. On the contrary, the successful jet airliner B707 and the DC-8 were launched respectively in 1958 and 1959, powered by the Pratt & Whitney JT-3 and JT-4. In 1959 Rolls Royce also powered the Sud Aviation Caravelle. General Electric also experimented with entry, by powering the unsuccessful Convair 880 and 990, which survived in the market only for a few years.

The transition towards the second period (1967-1980) is defined by the successful entry into the market of two large competitors: General Electric and Snecma. They created a joint venture, CFM International, to develop the CFM56 engine (Hayward, 1986). In 1970 General Electric also entered the market as an independent producer by introducing the CF6 series of engines.

This stage witnessed the birth and development of new market segments for the turbojet engine technology. The continuous improvement in the efficiency of the jet engine lowered the range and size at which the jet could compete with the turboprop. At the upper end the introduction of the big fan engines allowed wide-body aircraft such as the B747 to enter the market.

By the 1980s noise and pollution regulations, fluctuating fuel prices and airline deregulation became the main determinants of the technical evolution. Entrants at this stage are Textron in 1981, which serves a small niche of the market; Japanese Aeroengines, MTU and Fiat Avio in 1989, which entered the International Aeroengine cooperation dominated by the incumbents Pratt & Whitney and Rolls Royce; and Allison in 1995 in the small jet segment[6]. Technology is a major driver of competition. Post-sales support, in terms of ease of service, maintenance, product reliability, parts availability and long-run minimisation of operating costs, is also an increasingly important competitive factor.

3.2 Market stability

The history of the commercial jet engine industry from 1958 to 1997 witnessed a few events of entry in all the stages and no exit.

The industry evolution shows a decreasing level of concentration (Figure 1). At the first stage the industry structure was characterised by a quasi *stable duopoly* dominated by Pratt & Whitney (Figure 2) and by a clearly high level of concentration[7]. In the second stage, the industry moved from a duopolistic to an oligopolistic structure, characterised by intense rivalry. Engine manufacturers competed in terms of customers and new products. They strove to get into the market with launch engines for new aircraft. The level of concentration decreased because of this entry of new large competitors. At the third stage we still observe an oligopolistic industry characterised by the presence of intense competition among four large players and by minor entries that do not destabilise the industry. The level of concentration decreases and tends to stabilise at a relatively low level.

Figure 2 shows the dynamics of market shares over the entire period. While during the first and second stage the leader maintains its position, the last stage is clearly marked by mobility of market shares among all major incumbents. The Pashigian index of market shares' instability in the three periods also shows increasing instability over time (Table 1), and provides information about the source of instability in the different periods. While in the second period entry caused instability of market shares, in the third turbulence is determined by competition among incumbents. This shows that the reduction in the level of concentration is not determined by entry, but by the establishment of a shared oligopoly among the incumbents.

The examination of the change in the rank of players also confirms this pattern (Table 2). The first stage displays invariance of the players' position as indicated by the presence of very high values on the diagonal of the matrix. In the second stage the leader maintains its position, while entrants destabilises the second player position. In the last there is a high level of turbulence in the rank: the leader loses its position and mobility is high at all levels.

Taken together, all these measures show a quite unusual picture of a Schumpeterian dynamics of an industry: instability characterises the later stages of industry evolution while concentration decreases instead of increasing.

---

[6] In 1995 Allison was taken over by Rolls Royce. For the purpose of this study, we treat Allison as an independent producer, since decisions on the launch of new products are usually taken at least 5 years before the commercial introduction.

[7] For the computation of market shares, we had to choose if considering the cooperation as a single actor or if considering all the actors within the cooperation. Even if there are not significant differences in the results of the analysis, in this paper we adopt the second option, because this gives a better description of the relative positions of players. Market shares and actor centrality, the units of analysis of the industry and network measures used, are divided according to the share of the actor in the joint venture.

Figure 1. Jet engine industrial concentration

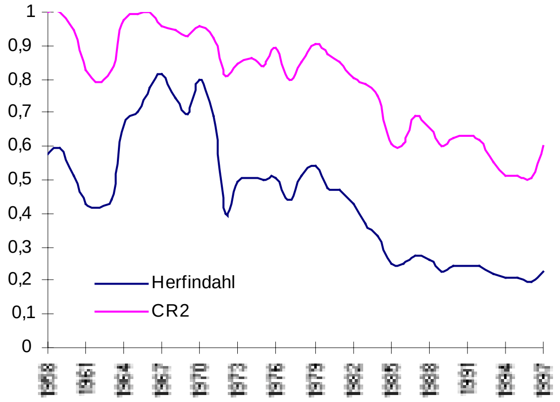


Figure 2. Dynamics of market shares

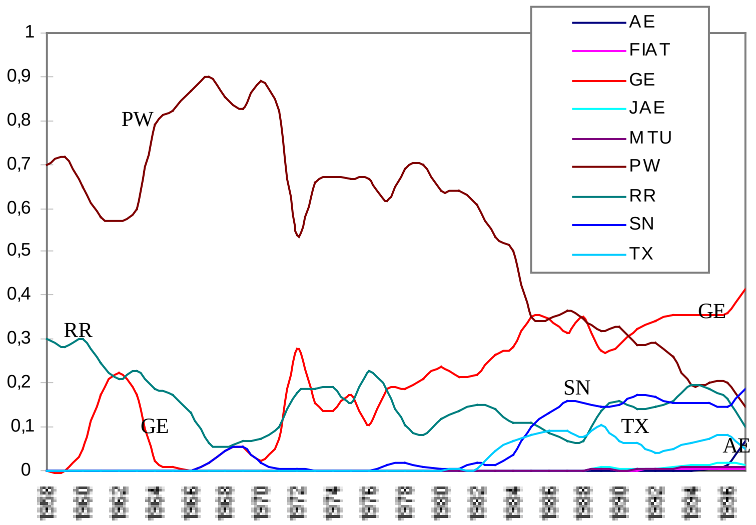


Table 1. Market shares' instability by entrants and by incumbents

	1958-1966	1967-1980	1981-1997
Pashig	0,15	0,28	0,53
Pashig by entry	0,15	0,24	0,15
Pashig by incumbents	0,00	0,04	0,38

Table 2. Turbulence of the players' position

1958-1966

	#1	#2	>2
#1	*1*	0	0
#2	0	*0,89*	0,11
entry	0	0,11	*0,89*

1967-1980

	#1	#2	>2
#1	*1*	0	0
#2	0	*0,43*	0,57
entry	0	0,36	*0,64*

1981-1997

	#1	#2	#3	#4	>4
#1	*0,53*	0,41	0,06	0	0
#2	0,59	*0,41*	0	0	0
#3	0	0,12	*0,53*	0,24	0,12
#4	0	0,12	0,41	*0,29*	0,18
entry	0	0	0,02	0,15	*0,83*

3.3 Increasing returns in the jet engine industry

In this paragraph we try to understand the dynamics of firms' competition by investigating the existence of positive feedback in their activities: in *design and manufacturing*, through an analysis of data on the pattern of introduction of products, and in *marketing* through information on the competitive factors driving the relations with the final demand, i.e. the airline companies.

Table 3 shows the number of programs and versions in operation and introduced (new) in the commercial jet engine and aircraft industries in the periods under analysis. At the first stage few engine programs and versions were introduced. The first programs had previously been developed for military use. The variety of solutions proposed was low, because given technical and market uncertainty and limitations of resources and time, undertaking different new design programs was practically impossible. Technological innovation and birth of new segments contributed to a growing product variety in the second stage. The growth of the number of programs, models and versions was evident with respect to the first period. At the final stage, the rate of introduction of new products is still very high.

Unlike industry life cycle patterns, characterised by an increasing standardisation of products and a reduction of the rate of product innovation, this industry exhibited a continuous introduction of new products in different technological sub-trajectories. In many cases, the yearly average number of products introduced is increasing over the three periods.

A similar pattern is observed in the commercial aircraft industry.

The decomposition of the products and versions by entry period provides interesting elements to understand the dynamics of *competition between entrants and incumbents*. While it is said that entry accounts for most of the product innovations, in the jet engine industries the largest part of new products and versions introduced in the second and third stages come from the early entrants (INC1). Entrants in the second stage (INC2) maintain a lower rate of introduction of products also in the third stage.

This reveals variety in firms' innovation rates and provide evidence of the existence of increasing returns to product R&D. Accumulation of knowledge, experience in organisation of production, higher rates of cost reduction represent cumulative advantages for incumbents in the innovative activity.

Again, the aircraft industry shows a similar pattern.

The statistics on number of engine versions and number of applications (aircraft programs and versions) per engine program give evidence of the existence of *economies of scale and scope in product development* activities. Jet engine companies develop families of product designs, based on the concept of "robust design" (Rothwell and Gardiner, 1989, 1990). Robustness occurs in terms of adaptability of the basic design to different customers and to different market segments. It allows some degree of economies of scale (high commonality of parts) and scope (high product variety) on the R&D and production side and offers the possibility of enhanced learning from user experience. In fact users, working with similar platforms, can be more apt to ask for specific modifications of design. This type of design applies not only to sequential introduction of models, but also to different more or less contemporaneous versions.

Sutton (1998) documents the presence of economies of scope in aircraft design by showing data about the non recurring costs of the B747 and its versions. He comments: "When a commercial jet is directly derived from its predecessor, its development cost may be less than 20 percent of its parent's. Even when planes are only distantly related, the degree of commonality, and so the level of cost savings, may be substantial".

Table 3. Entry and product introductions

	ENGINE			AIRCRAFT		
	1958-1966	**1967-1980**	**1981-1997**	**1958-1966**	**1967-1980**	**1981-1997**
N° of manufacturers	3	4	9	8	11	9
Entry	3	2	5	8	5	3
Exit	1	-	-	2	5	2
N° of programs	7	11	16	8	19	30
average	0,78	0,79	0,94	0,89	1,36	1,76
entry	*7*	*2*	*3*	*8*	*13*	*3*
INC1		*9*	*9*		*6*	*15*
INC2			*4*			*12*
N° of new programs	7	6	8	8	11	17
average	0,78	0,43	0,47	0,89	0,79	1,00
entry	*7*	*2*	*3*	*8*	*6*	*3*
INC1		*4*	*3*		*5*	*7*
INC2			*2*			*7*
N° of versions	18	48	96	55	130	115
average	2,00	3,43	5,65	6,11	9,29	6,76
entry	*18*	*10*	*11*	*55*	*25*	*5*
INC1		*38*	*53*		*105*	*76*
INC2			*32*			*34*
N° of new versions	18	38	64	55	102	70
average	2,00	2,71	3,76	6,11	7,29	4,12
entry	*19*	*10*	*11*	*55*	*24*	*4*
INC1		*28*	*30*		*78*	*47*
INC2			*23*			*17*

The development of the A330 and A340 by Airbus is another example of the concept of product families. The A330 and A340 share the same wing, cockpit, tail unit and fuselage, but are used in different markets. They also have much in common with the previous programs A300/A310 and A320 (*Jane's All the World Aircraft,* 1987-88). In this case, commonality occurs even across different programs.

We give some measures of the degree of *robustness of basic designs* (programs) as an indication of the presence of economies of scale and scope in design and manufacturing activities of aircraft and engine companies. The comparison between jet and prop aircraft and engine industries represents a benchmark for evaluating and interpreting the data on the jet engine industry.

Table 4 shows data on average, standard deviation and maximum number of versions per program in the turbojet and turboprop industry. The average and the maximum number of versions per program in the jet is higher than in the prop, both in aircraft and engine[8]. In addition, the number of programs in turboprop is higher than in turbojet, although the size of the market is smaller. This suggests that the turboprop market is more fragmented in different programs and that the degree of economies of scale and scope is much lower[9]. Given the heterogeneity of technical and market characteristics of different programs, economies of scale and scope are obtained by introducing subsequent versions of the same program, more than by developing many programs. The higher standard deviation in the jet industries also indicates a more disperse distribution of the number of versions per program, motivated by the presence of a number of "robust" programs with many versions, and of a few programs, mainly in the regional market, with only one or two versions.

It is evident that the turbojet technology is more characterised by processes of extensions of product families based on the exploitation of shared design knowledge.

Finally, in table 5 we show for the three periods of the jet industry evolution data on the number of *versions* and the number of *applications* (aircraft programs and versions) per engine programs. Data on the number of applications present further evidence on the existence of increasing returns to product R&D. The number of aircraft programs per engine program gives a first indication on the width of different applications of the same program, while the number of aircraft versions represents the totality of applications for each engine. Over the three stages the values are increasing, suggesting the increasing reliance on robust design practices. Companies try to design engines that can be stretched for different applications, while they introduce new programs to cover new market segments or to integrate highly innovative technologies. Only the statistics on the number of aircraft versions are decreasing in the last stage. They reflect the peak of introduction of aircraft versions in the second stage, explained by a very high number of versions of the B707 and DC-8 introduced at the end of the 1960's, to meet the requirements of many different operators which started to buy commercial jet aircraft (airlines, governments, service companies, military operators).

[8] As the distribution of the values is not normal, the t-test for the equality of means is not valid. We carried out the Mann Whitney U test of two independent samples, for each couple of means. The means of jet engine and prop engine resulted significant at the level of 1%. For jet engine and jet aircraft the means are not significantly different. This confirms the observed similarity in the basic design characteristics of the two products.

[9] The segmentation of turboprop engine industry is analysed in Bonaccorsi and Giuri (2000a).

Table 4. Number of versions per program in the jet and turboprop industries

	jet engine	prop engine	jet aircraft	prop aircraft
number of programs	21	32	36	38
number of versions	120	77	229	128
average number of versions per program	5,71	2,41	6,36	3,36
standard deviation	4,94	1,89	7,39	2,95
max	16	9	38	15

Table 5. Number of applications per engine program

	1st	2nd	3rd	All
average number of engine versions per engine program	2,57	4,36	6,00	5,71
standard deviation	1,40	3,47	4,90	4,94
max	5	13	15	16
average number of aircraft programs per engine program	1,86	2,55	3,19	3,00
standard deviation	0,83	1,50	2,21	2,25
max	3	6	7	7
average number of aircraft versions per engine program	8,29	13,00	10,00	13,38
standard deviation	9,13	10,24	9,77	14,36
max	30	31	40	46

In marketing, jet engine companies relate with two layers of demand: the aircraft manufacturers and the airline companies.

Network effects exist in the acquisition of engines by airlines. Buying an engine from the same supplier may bring about cost savings due to commonality across different engines and easier availability of spare parts. Maintenance and service activities will also be cheaper. Positive network externalities derive from the installed base of an engine, which enlarge the network of spare parts and maintenance services. Sutton (1998) observes the same effect in the relation between aircraft manufacturers and airlines. The impact of this effect is to further increase the lower bound to concentration.

In recent years, the increasingly specific technical requirements for maintenance are pushing airlines, which are more focused on cost efficiency, toward using specialist companies. They have started to outsource maintenance activities and inventory of spare parts to engine manufacturers, which are also introducing programmes of logistics and materials management (Lynch, 1984). Engine companies are aggressively expanding maintenance activities by creating their own service subsidiaries and through a series of joint ventures with the air carriers (*Flight International*, various years). They can pursuit economies of scale by offering after-sales, spare parts, repair and management services to many customers. This activity is particularly advantageous for companies with a large installed base.

The two sets of evidences on product introductions and network effects in the airline industry clearly suggest the existence of increasing returns.

The comparison between jet engine and jet aircraft is particularly interesting. It shows similarity in structural technical and market characteristics but differences in the industries' structures and dynamics. Precisely, the two industries shows the same conditions for increasing returns: first, they display similarity in the patterns of introduction of products favouring incumbents; second, increasing returns to marketing activities are present in both industries, as they share the same final customers. The structural dynamics of the two industry is, on the contrary, very different: while the jet aircraft industry witnessed a tremendous process of concentration together with exit of major players, in the jet engine industry the level of concentration decreased and the final market structure was marked by instability of market shares and turbulence of the players' positions.

Why does the jet engine industry show a different pattern? Why do return conditions have not the same effect in the jet engine industry? How do increasing returns and persistence of differentiated innovative performances at firm level coexist with an unstable market structure and a turbulent dynamics of market shares?

3.4 Dynamics of vertical relations

Evolutionary contributions propose that coordination through market institutions coevolve with technology and firm specific factors to determine the evolution of industries (Nelson, 1994). In vertically related industries the network of vertical relations between buyers and suppliers is a market mechanism influencing the dynamics of the supplier industry.

We first show the evolution of the vertical relations from the buyer side, that is the adoption of single or multiple sourcing by aircraft manufacturers. Then we present the overall structure of vertical relations, shaped by the evolution of technology and of sourcing strategies.

3.4.1 Sourcing strategies

The pattern of sourcing of aircraft manufacturers changed considerably over the industry evolution. Two levels of analysis deserve attention: company level and program level.

While at the birth of the industry aircraft makers tended to operate through single sourcing, or in some cases dual sourcing for specific aircraft models, the solution of the major technical problems of the first stage of industry evolution, while reducing the degree of uncertainty, allowed designing aircraft to integrate different engine configurations. Innovation at the design level permitted the increasing interchangeability of engines on newer model aircraft (Bluestone et al., 1981). Airframes started to be built to accept any one of several turbine configurations offered.

This trend led to the shift from single to dual and multiple sourcing strategies of large aircraft manufacturers (Figure 3). Multiple sourcing policies began to be adopted at the aircraft program level. This played a key role in the dynamics of competition among entrants and incumbents. Major engine companies attempted to enlarge their market by supplying different users, especially all the big aircraft manufacturers (Boeing, Douglas and the late entrant Airbus).

There are several reasons explaining multiple sourcing strategies of aircraft manufacturers[10]. First, in the turbojet industry there is a strong pressure from airlines for having multi-engined aircraft. In fact, airlines operating jet aircraft exert a powerful influence on the selection of the engines. Since airlines operate across many seat-range segments, their costs (mainly for maintenance and pilot training) are heavily influenced by the diversity of both aircraft and engines. By pushing towards multiple sourcing of engines on the same aircraft model they gain flexibility in selecting engines that are consistent with previous aircraft models, even from other manufacturers, and try to minimise their costs across the whole fleet.

As it will be better explained in the next paragraph, a change in the locus of learning – *from single relations to learning from heterogeneity* – is a major factor explaining the switch from single to multiple sourcing of aircraft manufacturers. This is particularly relevant for developing the capability to answer the increasingly specific and differentiated requirements of airlines.

Alternative sourcing also provides advantages through the development of competition among suppliers, gives better information about suppliers' cost and performance capabilities and increases the opportunity for innovation. It also creates an insurance policy for cases of demand peaks, particularly important in an industry characterised by discontinuous demand.

However, dual or multiple sourcing is only possible when high suppliers' up-front costs can be recovered over large volumes. In fact, as displayed in figure 4, many minor companies which survived for a short period in the industry never adopted multiple sourcing strategies.

Table 6 shows the number of programs in single and multiple sourcing in the three stages. The number of aircraft in dual sourcing increases in absolute terms during the three stages. In the final stage, four aircraft programs integrate engines from three different suppliers. At the same time the number of aircraft in single sourcing stays high. This reflects the data on single sourcing at the manufacturer level.

---

[10] Costs and benefits of buyers' adoption of single, dual and multiple sourcing have been examined by economic scholars, most of them addressing the analysis of the defence procurement process (Demski et al., 1987; Farrell and Gallini, 1988; Anton and Yao, 1987, 1992; Riordan and Sappington 1989) and in the management of supply relations (Bailey and Falmer, 1982; Richardson, 1993, Hines, 1994).

Figure 3. Jet aircraft manufacturers adopting multiple sourcing

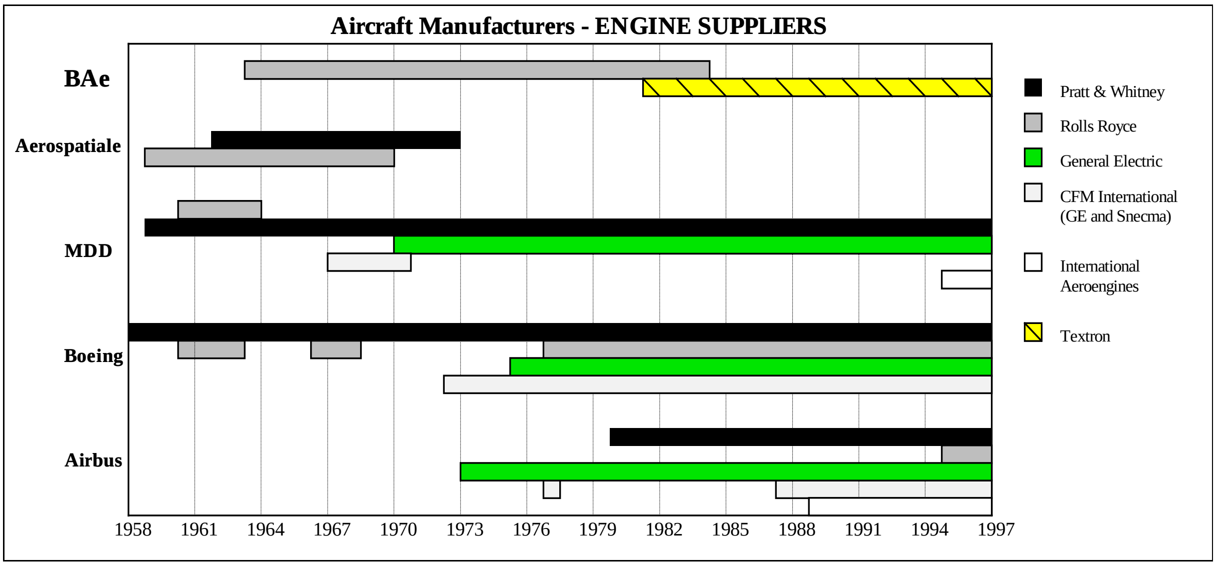


Figure 4. Jet aircraft manufacturers adopting single sourcing

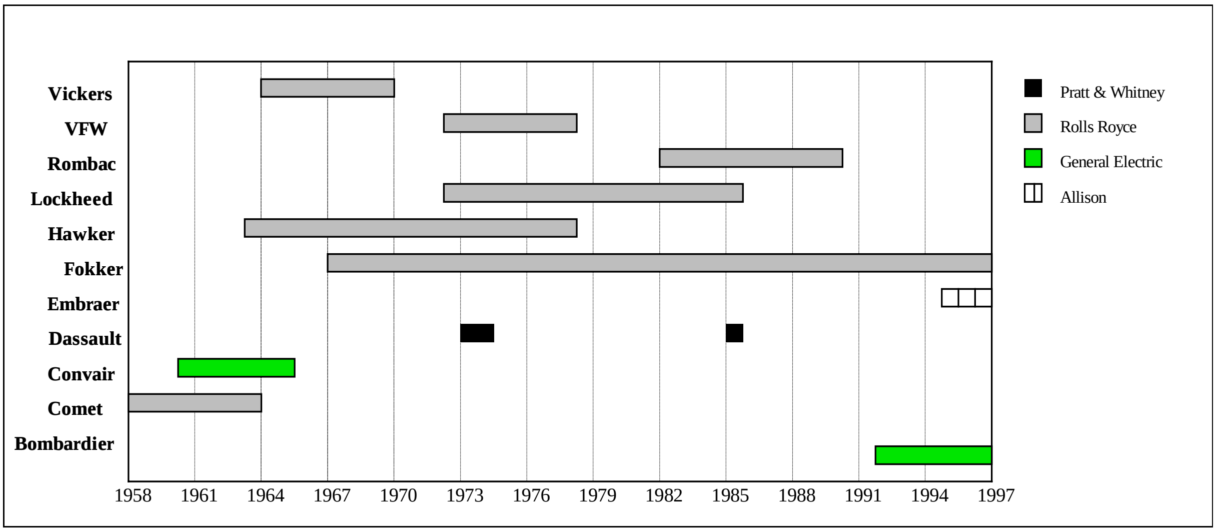


Table 6. Number of suppliers per aircraft program

Number of suppliers	1958-1966	1967-1980	1981-1997
1	4	11	16
2	4	7	10
3		1	4
Total	8	19	30

3.4.2 The structural evolution of network

The network dynamics is represented by measures of relational density and of engine group centralisation for each year of the three periods. The network is decomposed into a *core* (= the subgraph including all the most central actors) and a periphery, in order to identify effects of structural differentiation and hierarchical organisation in the network.

We believe that the *process of creation of vertical linkages* captures the characteristics of technology and of the demand regime. On the demand side, policies of single, dual or multiple sourcing are reflected into the relational activity of customers. With respect to technology, the creation of relations and their stability over time reflect the technological learning which takes place within a single relation and from heterogeneous relations. The pattern of introduction of products for different applications is also reflected in the relations of suppliers.

The structure of the network at the beginning and in the year of transition between stages is shown in Figure 5.

In 1958-59 two suppliers created a *partitioned network*. Pratt & Whitney (PW) and Rolls Royce (RR) supplied aircraft manufacturers within close and stable relations. Relations were mainly one-to one on the part of the users, that operated through single sourcing (Figure 5, years 1959 and 1966). The fundamental nature of uncertainty implied that customers worked closely with a single engine supplier in order to figure out the viable configuration.

In turn, the two actors built and interrupted relations. Some cases of dual sourcing occurred for specific versions of aircraft programs. These relations were typically characterised by short duration and instability, and by small quantities exchanged (weak ties). An example was the integration of the turbofan Rolls Royce Conway in one version of the B707 and DC-8. These relations lasted a few years, because in the meanwhile Pratt & Whitney, first supplier of Boeing and Douglas, developed a turbofan, and regained the position of single supplier.

By means of exclusive relations, both aircraft and engine manufacturers learnt the feasibility of jet technology and greatly reduced the uncertainty. This *demonstration effect* opened new opportunities to entry. Customers began to accept the idea of breaking exclusive relations and worked with more engine suppliers. It was no longer a matter of demonstrating one basic design, but of developing the new technology over many size and thrust dimensions. The nature of uncertainty changed. Consequently, once the feasibility was demonstrated, the resolution of uncertainty in stage 2 called for the exploration of a variety of *applications*. Each application depended on specific requirements of new market segments and on the addition of new functions beyond the basic ones (e.g. reduction of noise, pollution control, safety, reliability). New technical solutions did not need to be developed within a single relation. On the contrary, large customers had an interest in opening relations with many engine suppliers, exploiting different technical capabilities. Here a strong effect of *learning from heterogeneity* can be found.

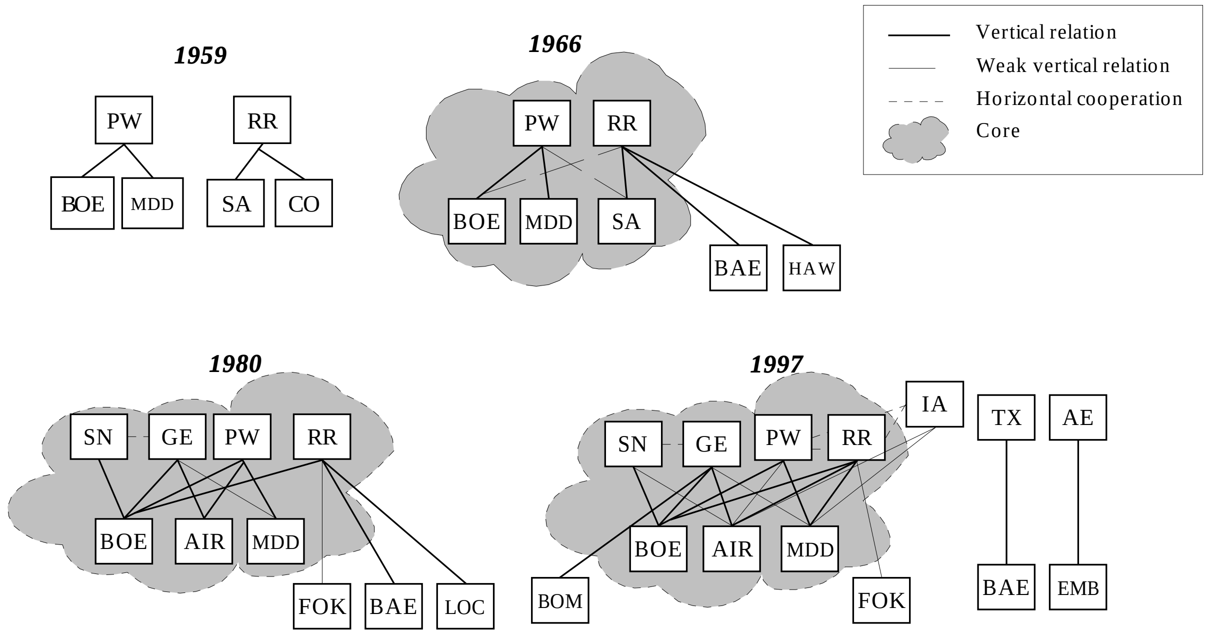
The network changed its structure completely (Figure 5, year 1980). Each customer looked for supply relations with more than one engine manufacturer and opened new relations. The dynamics of network reflects the evolution of underlying technology. On the supplier side, the introduction of robust designs brought about the possibility to adapt the product to the evolving needs of different users.

In stage 2 the structure of the network allowed all engine suppliers to get access to central customers. They had the opportunity to work on challenging technical requirements of customers and were able to access the relevant technology for application. This “equalisation” of opportunities had a stabilising effect on the network in stage 3 (Figure 5, 1997). On the other side, technological innovations could rapidly be made available to all aircraft manufacturers.

Once engine manufacturers gained a structural position of access to all major aircraft manufacturers, the focus of competition shifted to the second layer of the vertical network, represented by the airline companies. Therefore, the dynamics of quantities associated with each relation was determined by two factors: first, by technological advances and by the rate and speed of introduction of new products meeting the requirements of final customers; second, by the level of post-sales support and maintenance services offered to airlines.

A periphery of the network was also created by aircraft and engine manufacturers with single relations, which operated in the regional market.

Figure 5. Network structure in 1959-1966-1980-1997[11]



The dynamics of network in each year is displayed by the level of relational density for the entire network and for the core and by the group centralisation index.

In 2-mode networks the change in density depends on relational activity of suppliers, sourcing of

[11] Company names are reported in the Appendix.

customers and entry and exit of firms. Specifically, density increases because of new relations by incumbents, exit of firms with a number of relations below the average, entry of firms with a number of relations above the average. Density decreases because of interruption of relations by incumbents, exit of firms with a number of relations above the average, entry of firms with a number of relations below the average. As entry and exit is more likely to occur with a small number of relations, more generally density increases because of increasing relational intensity and decreases because of entry. Figure 7 presents the decomposition of the index which disentangles the effects on density of entry of new actors (denominator) and of increasing relational activity (numerator).

In the first stage density decreased because of entry of actors with a single relation. In the core of the network the density was also close to the maximum value (Figure 6)[12]. The group centralisation within the core shows that Rolls Royce and Pratt & Whitney presented similar levels of centrality. In some years the index was equal to zero at the core level, because the two actors had the same relational structure (Figure 8).

In the second stage the number of total relations slowly increased over the period (the numerator of the density index), while the number of possible relations (the denominator) firstly increased due to new entries, than oscillated due to exit of some aircraft manufacturers. The net effect was a reduction in density relative to the first period because of entry, from 1967 until 1972. After that period policies of multiple sourcing on the part of aircraft manufacturers multiplied the number of relations and led to a further increase in density (Figure 6). Within the core, the dynamics was similar but the number of new relations opened by central actors increased more rapidly. The group centralisation increased as General Electric and Snecma entered the industry with a low number of relations, creating inequality in the distribution of relations. After that, the diffusion of relations within the core reduced the value of the index.

In the third stage the level of relational density continued to be influenced by two opposite forces: the increasing number of relations created by the incumbents, and the entry of new companies with few (most often only one) relations. These forces determined respectively a growth and a reduction of the value of density around a stable value. As is clear from the decomposition of density, the number of possible relations in the core stabilised and remained unchanged over a 15-year period (Figure 7). While the density of the network still declined, although slowly, due to entries (Figure 6), the density of the core sharply increased and stabilised at high levels. This means that the network assumed a

[12]Measures in the first stage are more dependent on the small number of actors. More precisely, the indexes present a higher range of variation, because a single relation has a higher weight if the total number of relations is low. This is not a problem for our analysis, because network indicators embody information both on number of actors and on their relations. The indexes are normalised by size of the network, thus allowing for comparisons over time. Care needs to be exercised in interpreting changes in the first phase as indicators of very strong turbulence.

hierarchical configuration: those who were central actors in stage 2 were able to maintain and stabilise their structural position, while new entrants occupied a peripheral position, i.e. had few relations and those mainly with non-core actors.

Figure 6. Relational density and Group Centralisation

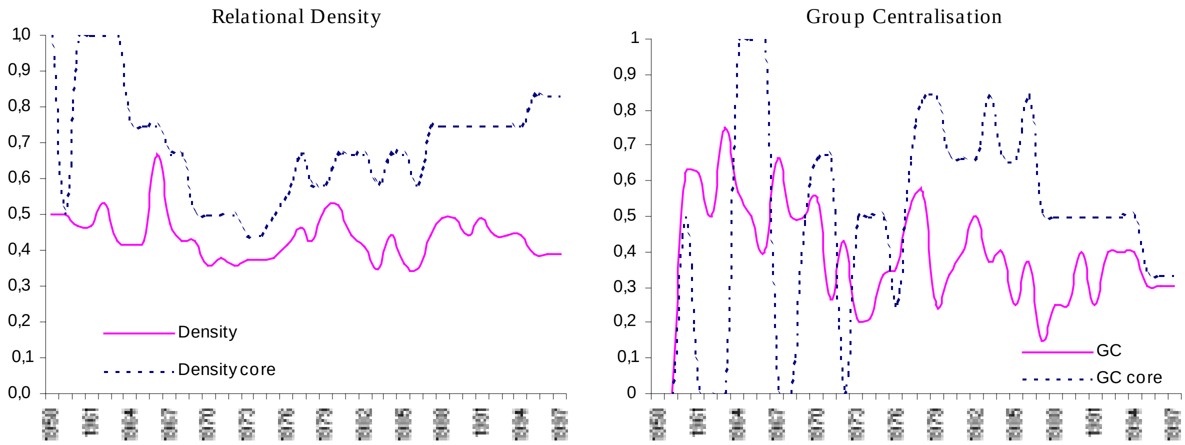
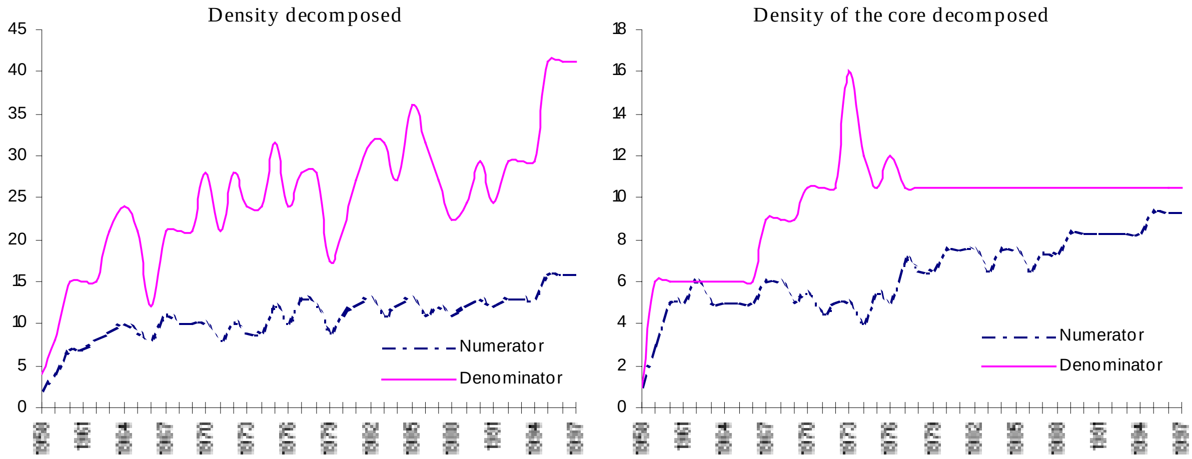


Figure 7. Relational density decomposed



4. Increasing returns and network dynamics

This case history offers an interesting example of interaction between technology conditions and vertical market structure, which prevent the effects of increasing returns to take place and explains the changing dynamics of market shares.

According to theories based on increasing returns, we would have expected to observe a high concentrated industry structure, characterised by dominance of the leader and stability of players positions. The basic reason is the possibility for incumbents to cumulate advantages over rivals. Our claim is that this possibility may be limited by the structure of the network.

Increasing returns to manufacturing lead to market dominance if demand is rapidly reallocated to more efficient firms. But if, as it is the case in many intermediate goods industries, long term contracts prevent rapidly demand reallocation, then the impact of cost superiority may be severely limited. It has been often noted that prices in intermediate industries with differentiated products tend to be *sticky*, i.e. they do not fluctuate as it would be necessary to clear the market. The reason is that in long term contracts the adjustment of prices does not take place on a continuous time, but rather at discrete points in time. For the same reason, there will be some delay in the reallocation of flows of demand from less efficient to more efficient firms. Thus we might expect that a stable network, exhibiting strong inertia of relations, will mitigate the impact of increasing returns and possibly prevent shakeout and growth of concentration.

However, in the long run this picture is not stable. In fact, while the inertia of long term contractual relationships and the resulting network stability might delay rapid adjustments in market shares, it is difficult to believe that in the very long run they could prevent a growth of concentration if persistent differences in cost structure existed. But persistent differences may be found only if firms can approach the technological frontier at different rates, due to heterogeneity in some underlying dimensions (say, managerial talent and organisational routines and competencies). We argue that the structure of the network has an impact on the persistence of differences of the firms' position with respect to the technological frontier. It is useful to introduce the notion of technological *sub-trajectory*, building on the more general notion developed by Dosi (1982).

In industries such as aircraft engine, each customer relation is a source of specific learning. Customers do not just "demand" products, but rather co-develop them, by specifying technical requirements and providing feedback on the integration between engine and airframe. In abstract terms, each customer relation develops over a specific technological sub-trajectory, with potential overlappings with other customer relations and sub trajectories. Technological capabilities of firms are determined not only by the level of investments in R&D, but also by the number and quality of customers they can access, that is, by the collection of technological sub-trajectories they can pursue. The adoption of multiple sourcing strategies of large customers offers opportunities for learning to all suppliers. The larger the number of customer relations, the richer the specific learning - an effect we call "learning from heterogeneity". Furthermore, the higher the degree of overlapping of sub-trajectories, the more similar are opportunities for specific learning across firms. All these effect are carefully reflected in the structure and dynamics of the network.

The emergence of a hierarchical network, with a core in which all firms access the same customers and the same technical and market opportunities, induces differences among firms to decrease. The process of hierarchisation of the network reduces the variety among firms and leads to a less selective environment. As opportunities are allocated to all suppliers in the core, market shares depend on short term fluctuation of demand and on incremental technical and marketing efforts directed to requirements of specific customers. Players positions are subject to modifications and the level of concentration decreases. The leader loses its position and its market share is aligned with the others.

This is a clear case in which the network represents a market mechanism which prevents the cumulative effects of increasing returns to take place. The emergent structure of network explains the instability of the relative positions of players.

In the first stage, the magnitudes of initial relations determine the market shares of the two entrants. The size of the market (USA for Pratt & Whitney and Europe for Rolls Royce) is considered a key determinant of the initial market share distribution. Single sourcing leads to sticky buyer-supplier relations, characterised by a higher inertia of market shares.

In the second stage we observed that instability of market shares derives from entrants. In addition, the affirmation of multiple sourcing breaks exclusive relations of incumbents and amplifies mobility of market shares. The increasing density of the network in the final stage favours market share turbulence in the core. Given the hierarchical organisation of the network into a core and a periphery, minor entries do not destabilise the network (small number of relations) nor the industry (small quantities exchanged by entrants).

Within the core, market shares fluctuation is induced in the short term by inertia of relations, combined with fluctuations in orders of individual aircraft. In the long term, turbulence is induced by the fact that the core is not centralised around a particular firm, as a result of the process of equalisation of opportunities. In fact, the centralisation of core actors declines and finally stabilises at a very low level (see Figure 8). Although the core becomes more and more stable in terms of number of actors and relations, no central actor dominate over the others in terms of structural position. The relational equivalence of central actors explains the instability in market shares and the turbulence of the players' positions.

This suggest a somewhat different picture of a maturity stage in the evolution of industries than the picture portrayed by established theories. Instead of standardisation of technology leading to the emergence of dominant leaders based on economies of scale and scope, there is still heterogeneity in technical solutions. However all customers in the network have access to all suppliers and vice versa. This means that no supplier can dominate the industry by driving competitors out on the basis of cost advantages, but rather the dynamics of market shares are shaped by technological competition over application-specific solutions and differential levels of after-sales service. Instead of a stage of market domination by a few incumbents, following the shakeout of the industry, the final stage shows the persistence of several competitors which fiercely fight each other.

5. Conclusions and implications

The paper contributes to the understanding of the effects of increasing returns on the dynamics of industries. It explores the idea that properties at the level of firms coevolve with more aggregate properties at the level of market institutions in the dynamics of industries. Precisely, we propose that the structure of network limits the effect of increasing returns at the firm level.

We develop a set of empirical measures for a clear understanding of the evolutionary dynamics of the industry. First, we detect the presence of economies of scale and scope in the design and manufacturing activities of engine companies through the analysis of introduction of programs and versions in the aircraft and engine industry. Second, indicators of industry stability are computed to understand the dynamics of concentration and the market share instability, with a focus on the competition among entrants and incumbents. Finally, data and measures on the network of vertical relations between suppliers and buyers in two vertically related industries are used to provide a representation of the vertical market structure.

The empirical analysis shows that the final structure of the industry is characterised by a low level of concentration and instability of market shares, which coexist with the existence of increasing returns. This is quite unusual, especially if compared with the evolution of the commercial jet aircraft industry, which shares the same conditions for increasing returns, but witnessed a dramatic process of concentration.

In the jet engine industry the emergence of a hierarchical network leads to equalisation of technical and market opportunities of suppliers and prevents the effects of increasing returns to take place. It also explains the strong turbulence in the relative positions of players.

This story also provides some elements for understanding the dynamics of competition among large firms within an industry. Earlier cross-industry studies (Kaplan, 1954; Collins and Preston, 1961; Mermelstein, 1969; Gort, 1962; Prais, 1976) and more recent contributions (Geroski and Toker, 1996; Baldwin, 1995) find that stability in market shares is positively related with size and a certain degree of stickiness of the rank position is found for the first companies in the rank. Caves (1998) points out that, as these studies are cross-industry, clear implications on competition should be drawn from industry studies. The evolution of the jet engine industry shows how the emergence of a hierarchical configuration of the network reduces the first mover advantages and the effects of dynamic increasing returns. The equalisation of technical and market opportunities induces mobility in the players' position.

The equalisation of technical opportunities among actors in the core reflects the intense technological competition fuelled by the need of maintaining a strong position in terms of technical and marketing opportunities offered to the customers (aircraft and airlines companies). This will be subject of future research, aiming at analysing the rate of technical progress, measured by the main technical parameters of engines, and the position of actors with respect to the technical frontier. The comparisons of rates of progress and positions of actors in different network structures will provide the basis to test this hypothesis.

The applicability of the concepts and tools proposed in this paper is open to further research and other examples, some of which we are ourselves pursuing.

Appendix. List of Companies

Engine Manufacturers	
AE	Allison (RR)
GE	General Electric
IA	Fiat, Japanese Aeroengine, Motoren Turbinen Union (International AeroEngines)
PW	Pratt & Whitney
RR	Rolls Royce
SN	Snecma (CI)
TX	Textron
Aircraft Manufacturers	
AIR	Airbus
BAE	British Aerospace
BOE	Boeing
BOM	Bombardier
COM	Comet
EMB	Embraer
FOK	Fokker
HAW	Hawker Siddeley
LOC	Lockheed
MDD	McDonnell Douglas
SA	Sud Aviation
VIC	Vickers

References

Agarwal, R., 1998, Evolutionary trends of industry variables, International Journal of Industrial Organisation, 16, 511-525.

Alchian, A.A., 1963, Reliability of progress curves in airframe production, Econometrica 31, 679-693.

Anton, J.J., Yao, D.A., 1987, Second sourcing and the experience curve: price competition in defence procurement, Rand Journal of Economics, 18, 57-76.

Anton, J.J., Yao, D.A., 1992, Coordination in split award auctions, Quarterly Journal of Economics, 681-707.

Arthur, W.B., 1989, Competing technologies, increasing returns, and lock-in by small historical events, Economic Journal, 99, 116-131.

Arthur, W.B., 1994, Increasing returns and path dependence in the economy, The University of Michigan Press.

Baily, P., Farmer, D., 1982, Materials Management Handbook, Gower Publishing, Aldershot.

Baldwin, J.R., 1995, The Dynamics of Industrial Competition, Cambridge University Press, Cambridge

Bassanini, A.P., Dosi, G., 1998, Competing technologies, international diffusion and the rate of convergence to a stable market structure, IIASA Interim Report, IR-98-012, March.

Bluestone, B., Jordan, P., Sullivan, M., 1981, Aircraft Industry Dynamics. An Analysis of Competition, Capital and Labor, Auburn House Publishing Company, Boston.

Bonaccorsi A., Giuri P., 2000a, Non shakeout patterns of industry evolution. The case of the turboprop engine industry, Research Policy, 19, 243-269.

Bonaccorsi A., Giuri P., 2000b, Network Structure and Industrial Dynamics. The long term evolution of the aircraft-engine industry, Working Paper, Sant'Anna School of Advanced Studies, Pisa (under review).

Bonaccorsi A., Giuri P., 2000c, The long term evolution of vertically-related industries, International Journal of Industrial Organisation, forthcoming.

Bonaccorsi A., Giuri P., 2000d, Industry life cycle and the evolution of the industry network, Working Paper, Sant'Anna School of Advanced Studies, Pisa.

Borgatti, S.P., Everett, M.G., 1997, Network Analysis of 2-Mode Data, Social Networks, 19, 3, 243-269.

Bright, C.D., 1978, The Jet Makers, The Regence Press of Kansas, Lawrence.

Caves, R.E., 1998, Industrial organisation and new findings on the turnover and mobility of firms, Journal of Economic Literature, 36, 1947-1982.

Caves, R.E., Porter, M.E., 1978, Market structure, oligopoly, and stability of market shares, Journal of Industrial Economics, 23, 289-311.

Chandler, A., 1990, Scale and scope: the dynamics of industrial capitalism,

Collins, N.R., Preston, L.E., 1961, The size structure of the largest industrial firms, 1909-1958, American Economic Review, 51, 986-1003.

Constant, E.W., 1980, The origin of the turbojet revolution, The John Hopkins University Press, Baltimore and London.

David, P.A., 1985, Clio and the economics of QWERTY, American Economic Review, 75, 332-337.

David, P.A., 1997, Path Dependence and the quest for historical economics: One more chorus on the ballade of QWERTY, Discussion Papers in Economic and Social History, Number 20, University of Oxford.

Demski, J.M, Sappington, D.E.M, Spiller P., 1987, Managing supplier switching, Rand Journal of Economics, 18, 77-97.

Dosi, G., 1982, Technological paradigms and technological trajectories, Research Policy.

European Commission, 1988, European Economy, Bruxelles.

Farrell, J., Gallini, N.T., 1988, Second sourcing as a commitment: monopoly incentives to attract competition, Quarterly Journal of Economics, 673-694.

Farrell, J., Saloner, G., 1985, Standardisation, compatibility, and innovation, Rand Journal of Economics, 16, 70-83.

Freeman, L.C., 1979, Centrality in Social Network: I. Conceptual Clarification, Social Networks, 1, 215-239.

Geroski, P.A., Toker, S., 1996, The turnover of market leaders in UK manufacturing industry, 1979-86, International Journal of Industrial Organisation, 14, 141-58.

Gort, M., 1963, Analysis of Stability and Change in Market Shares, Journal of Political Economy, 51-63.

Gort, M., Klepper, S., 1982, Time Paths in the Diffusion of Product Innovation, Economic Journal, 92, 630-653.

Hayward, K., 1986, International Collaboration in Civil Aerospace, Frances Pinter Publishers, London.

Hayward, K., 1994, The World Aerospace Industry. Collaboration and Competition, Duckworth & RUSI, London.

Helpman, E., Krugman, P.R., 1985, Market structure and foreign trade. Increasing returns, imperfect competition and the international economy, The MIT Press, Cambridge, Massachusetts.

Hines, 1994, Creating World Class Suppliers: unlocking mutual competitive advantage, Pitman, London.

Hymer, S., Pashigian, P., 1962, Turnover of firms as a measure of market behaviour, Review of Economics and Statistics, 81-87.

IATA, 1956-1994, World Air Transport Statistics, Montreal, Canada.

Jacoby, N.H., 1964, The relative stability of market shares. A theory and evidence from several industries, Journal of Industrial Economics, 12, 83-107.

Jane's All the Worlds Aircraft, 1940-1997, Jane's Information Group, Sentinel House.

Joskow, J., 1960, Structural Indicia: Rank-shift analysis as a supplement to concentration ratios, Review of Economics and Statistics, 113-116.

Kaplan, A.D.H., 1954, Big enterprise in a competitive system, Washington.

Katz, M.L., Shapiro, C., 1986, Technology adoption in the presence of network externalities, Journal of Political Economy, 94, 822-841.

Klein, B.H., 1977, Dynamic Economics, Harvard University Press, Cambridge.

Klepper, S., 1996, Entry, exit and growth over the product life cycle, American Economic Review, 86, 562-583.

Klepper, S., 1997, Industry life cycles, Industrial and Corporate Change, 6, 145-181.

Klepper, S., Simons, K., 1999, The making of an oligopoly: firm survival and technological change in the evolution of the U.S. tire industry, mimeo.

Krugman, P. R., 1990, Rethinking international trade, The MIT Press, Cambridge, Massachusetts.

Krugman, P. R., 1994, Peddling prosperity, W.W. Norton & Company, New York.

Large, J.P., et al., 1976, Parametric equations for estimating aircraft airframe costs, Report R-1693-1-PA&E, Rand Corporation, Santa Monica.

Large, J.P., Hoffmayer, K., Kontrovich, F., 1974, Production rate and production cost, Report R-1069-PA&E, Rand Corporation, Santa Monica.

Liebowitz, S., Margolis, S.E., 1995, Path dependence, lock-in, and history, Journal of Law, Economics, and Organisation, 11, 205-216.

Lynch, J.J., 1984, Airline Organisation in the 1980s, Macmillan, Hampshire.

Marschak, T., Glennan, T.K.jr., Summers, R., 1967, Strategy for R&D: Studies in the Microeconomics of Development, Springer Verlag, Berlin.

Mazzucato, M., A computational model of economies of scale and market share instability, Structural Change and Economic Dynamics, 9, 55-83.

Mermelstein, D., 1969, Large industrial corporation and asset shares, American Economic Review, 59, 531-541.

Metcalfe, J.S., 1999, Business capitalism: Increasing returns and growth in enterprise economies, paper presented to ESSID, Cargese.

Miller, R., Sawers, D., 1968, The Technical Development of Modern Aviation, Routledge & Kegan Paul, London.

Mowery, D, Nelson, R.R., 1999, The sources of industrial leadership, Cambridge University Press.

Mowery, D.C., Rosenberg, N., 1982, The Commercial Aircraft Industry, in Nelson R., ed., Government and Technological Progress, Pergamon Press, New York.

Mowery, D.C., Rosenberg, N., 1989, Technology and the Pursuit of Economic Growth, Cambridge University Press, Cambridge.

Nelson, R.R., 1994, The coevolution of technology, industry structure and supporting institutions, Industrial and Corporate Change, 47-63.

Nelson, R.R., 1999, The sources of industrial leadership: a perspective on industrial policy, De Economist, 147, 1, 1-18.

Norris, G., Wagner, M., 1997, Giant Jetliners, Motorbooks International Publishers and Wholesalers, Osceola.

Peck, M.P., Scherer, F.M., 1962, The Weapons Acquisition Process: An Economic Analysis, Harvard University, Boston.

Phillips, A., 1971, Technology and Market Structure. A study of the Aircraft Industry, Heath Lexington Books, Lexington, Massachusetts.

Phillips, A., Phillips, P.A., Phillips, T.T., 1994, Biz jets. Technology and market structure in the corporate jet aircraft industry, Kluwer, Dodrecht.

Prais, S., 1976, The evolution of giant firms in Britain, Cambridge University Press, Cambridge.

Richardson, J., 1993, Parallel Sourcing and Supplier Performance in the Japanese Automobile Industry, Strategic Management Journal, 339-350.

Riordan, M.H., Sappington, E.M., 1989, Second sourcing, Rand Journal of Economics, 20, 1, 41-58.

Romer, P., 1991, Increasing returns and new development in the theory of growth, in Barnett, W.A., Cornet, B., D'Aspremont, C., and others, Equilibrium theory and applications, Cambridge University Press, Cambridge.

Romer, P.M., 1986, Increasing returns and long run growth, Journal of Political Economy, 94, 1002-1037.

Romer, P.M., 1990, Endogenous technological change, Journal of Political Economy, 91, 71-100.

Rosemberg, N., 1982. Inside the black box: Technology and Economics. Cambridge University Press, Cambridge.

Rothwell, R., Gardiner, P., 1989, The strategic management of re-innovation, R&D Management, 147-160.

Rothwell, R., Gardiner, P., 1990, Robustness and Product Design Families, in Oakley M., Design Management, Blackwell Reference, Oxford.

Rowe, B.H., 1993, A personal view of five decades of jet engines, World Aerospace Technology, 55-58.

Scott, J., 1991, Social Network Analysis, A Handbook, Sage, London.

Sutton, J., 1998, Technology and Industry Structure, MIT Press.

Vincenti, W.G., 1990, What Engineers Know and How They Know It. Analytical Studies from Aeronautical History, The John Hopkins University Press, London.

Wasserman, S., Faust, K., 1995, Social Network Analysis: Methods and Applications, Cambridge University Press, Cambridge, UK.

Windrum, P., Birchenall, C., 1998, Is product life cycle theory a special case? Dominant designs and the emergence of market niches through coevolutionary learning, Structural Change and Economic Dynamics, 109-134.

Technical press

Flight International, 1996, Leaving home, 6-12 Nov., 37.

Flight International, 1996, Tracking down spare parts, 52-53.

Flight International, 1997, Maintenance hots up with two sales and Boing's China move, 20-26 Aug., 1997.

Flight International, 1997, Snecma takes on GE in push to double CFM56 maintenance, 26 Nov.-2 Dec., 22.

Flight International, 1997, Spare a thought, 19-25 Feb., 33-34.

Flight International, 1997, Special relation, 2-8 Apr., 28.

Flight International, 1998, GE overhaul network continues to expand, 16-22 Sep., 24.

Flight International, 1998, Muscling to the market lead, 14-20 Jan., 52-53.

Flight International, 1998, Parts partnership, 12-18 Aug., 36-42.

Flight International, 1998, R-R and American in US maintenance venture, 21-27 Jan., 8.

Flight International, 1999, Snecma closes in on airline maintenance contracts, 3-9 Feb., 27.