# INDUSTRY LIFE CYCLE
# AND THE EVOLUTION OF INDUSTRY NETWORK

ANDREA BONACCORSI*
PAOLA GIURI**

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ANDREA BONACCORSI*
PAOLA GIURI**

**Faculty of Economics, University of Pisa*
***Scuola Superiore Sant'Anna, Pisa*
*SPRU, University of Sussex*

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## Abstract

The paper develops a case history of the world commercial jet engine industry (1958-1997). The structural evolution of this industry shows significant anomalies with respect to key predictions of models of industry life cycle (ILC): the birth of the industry is not associated to high variance in product designs and to significant entry; the dominant design stage is not associated to exit, but rather to entry; the maturity stage is not characterised by stability but rather by extreme turbulence. These anomalies raise interesting theoretical and empirical questions. We suggest an integration with the existing theories which takes into account simultaneously the evolution of *technology* and *market demand*. In many industries the structure and dynamics of market relations heavily influence the evolution of technology and shape the structural dynamics of the industry. This is particularly true when, as in the case of many intermediate good industry, market demand is *heterogeneous*, *discontinuous* and *relation-intensive*. To take into account these features, we propose to analyse the properties of the *network* connecting vertically related industries. A network can be represented by a bipartite graph, with an associated biadjacency matrix whose rows and columns describe exchanges at the level of *individual* suppliers and customers. We provide data on the structure of the network of vertical relations between engine suppliers and airframe manufacturers during the entire life of the jet engine industry and demonstrate that changes in the structure closely follow the transition path over the stages of the life cycle. We also try to relate network measures to industry measures in three stages of ILC. We explore the relationship between density and concentration at the industry level and between actor centrality and market share at the company level. Results show that the relation between network and industry measures closely follows the time periodisation of ILC.

*Faculty of Economics, University of Pisa, via Ridolfi, 10, I-56100 Pisa, Italy.
Phone: +39.50.945311, fax: +39.050.541403, e-mail: abonacco@ec.unipi.it
**Scuola Superiore S.Anna, via Carducci, 40, I-56127 Pisa, Italy.
Phone: +39.50.883345, fax: +39.50.883344, e-mail: giuri@sssup1.sssup.it
SPRU - Science and Technology Policy Research, Mantell Building, University of Sussex, Falmer, Brighton BN1 9RF.
Phone: +44.1273.686758, fax: +44.1273.685865, e-mail: P.Giuri@sussex.ac.uk

# 1. Introduction

This paper addresses the problem of the general validity of models of industry life cycle. A detailed counter-example is illustrated with reference to the entire history of the world commercial jet engine industry (1958-97).

The structural evolution of this industry shows some anomalies with respect to key predictions of the model. First, in the initial stage there was no massive entry and the exploration of a variety of design configurations was limited. Rather, a small proportion of potential entrants actually entered the industry and each of them developed a single application in strict cooperation with a major customer. Second, the emergence of a dominant design was not followed by the industry shake-out, but rather by new entries. Third, the final stage witnessed the stabilisation of the number of main competitors and of the level of concentration but also, contrary to the theory, a highly turbulent dynamics of market shares among incumbents.

As these anomalies are difficult to reconcile with the established life cycle theory, we suggest an integration which takes into account simultaneously the evolution of *technology* and of *market demand*. In many industries the structure and dynamics of market relations heavily influence the evolution of technology and shape the structural dynamics of the industry. This is particularly true when, as in the case of many intermediate good industry, market demand is *heterogeneous*, *discontinuous* and *relation-intensive*.

To take into account these features, we propose to analyse the properties of the *network* connecting vertically related industries. A network can be represented by a bipartite graph, with an associated input-output matrix whose rows and columns describe exchanges at the level of *individual* suppliers and customers. We provide data on the structure of the network of vertical relations between engine suppliers and airframe manufacturers during the entire life of the jet engine industry and demonstrate that changes in the structure closely follow the transition path over the stages of the life cycle.

After a brief review of the limits of ILC models we develop the industry case study. In section 3 data on network dynamics are introduced and discussed, section 4 develops an explanation of the industry life cycle in terms of network dynamics and section 5 offers some implications and conclusions.

## 2. The limits of industry life cycle models

The general applicability of the industry life cycle model is subject to much debate in industrial organisation and economics of innovation.

Originally, the model was proposed as an empirical generalisation on the basis of stylised evidence regarding the evolution of industry structure in the long run. The development of the underlying product and process technologies explains the unfolding of qualitatively different stages. Structural change of the industry depends on the process of learning by firms of new product designs and new manufacturing techniques. Over time, the development of technology affects the expected rate of return of investment into search activities in the space of design parameters. Eventually, the return from additional search decreases, so that a subset of product configurations emerges as the dominant solution (Abernathy and Utterback, 1975).

Consequently, the initial stage of ILC is characterised by massive *entry* of new firms, while there is no advantage arising from a larger firm size. Each entrant may explore different design configurations, none of which is dominant. As a dominant design emerges, opportunities for exploration sharply decrease, while product standardisation allows the exploitation of economies of scale in manufacturing. Consequently, the rate of entry drastically decreases, while part of the incumbents experiences exit. The net result is an increase in concentration. Finally, after the industry shake-out, the industry stabilises over a configuration in which incumbents may prevent entry and enjoy stability in market shares.

Along this line, a number of studies analysed the pattern of entry and exit over the ILC (Gort and Klepper, 1982; Klepper and Graddy, 1990; Agarwal and Gort, 1996). Within a different context, the same pattern has been proposed for the dynamics of organisational density (Hannan and Carroll, 1992).

The stages of ILC can be naturally interpreted as transition paths from Schumpeter Mark I to Schumpeter Mark II regimes (Nelson and Winter, 1982; Malerba and Orsenigo, 1995).

One of the key predictions of life cycle models- namely, the emergence of dominant design, can be also obtained on the basis of theories of variety in the economy at large (Saviotti, 1996). In this view, the process of economic development requires the continuous growth of product variety, as described in a space of characteristics. The emergence of dominant design is visible in the tendency of products to converge on a narrow region of the space of characteristics. This, however, does not reduce overall variety, but rather creates competition among similar product design, pushing firms to escape towards niches of the space which do not present intense competition.

Recently, the predictions of the life cycle hypothesis have been replicated via a formal model (Klepper, 1996). So far, the model of life cycle evolution has been tested empirically in a large number of industries, which, however, share the common feature of mass production (Utterback and Suarez, 1993; Jovanovic and MacDonald, 1994; Greenstein and Wade, 1998).

This has created a lot of interest on the general applicability of the model to other industries. Since life cycle models are one of the few empirical generalisations available on the long run evolution of industries, research into this field is clearly warranted.

There are several arguments that limit the applicability of industry life cycle models (Malerba and Orsenigo, 1996; Bonaccorsi, 1996).

First, the *distinction between product and process innovation* which is typical in mass-production industries has not the same meaning in other industries. Klepper (1997) has made clear that the applicability of industry life cycle models is limited to the cases in which technology opens opportunities for product and process innovation *simultaneously*. In fact, in mass production industries the emergence of a dominant design reduces uncertainty over physical parameters of product design and increases the profitability of process innovations. On the contrary, in many 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. This situation applies to industries such as large equipment and capital goods, telecommunication system, energy infrastructure, construction, railway and other transport systems. Similarly, in industries such as large gas turbines, aircraft and aero-engines, companies try to minimise variations in design and maximise the total output but, because of demand discontinuity, cannot rely on large volumes in order to plan the production activity.

Since products are highly customised, process technologies are mainly of generic type, skilled labour-intensive, rather than automated. 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.

Basically, these non-mass production industries are permanently located in the upper-left part of the product-process matrix proposed by Hayes and Wheelwright (1990). There is no evidence of an intrinsic tendency of non-mass production industries to move downward across the matrix. Therefore, for a large portion of modern manufacturing, one of the basic assumptions of ILC models simply does not apply.

Second, 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 clearly true for most consumer industries and for part of intermediate industries, is far from being general. This characterisation of demand regime heavily underscores three factors: market demand may be highly *heterogeneous*, may take place *discontinuously*, and may require *relational investments*.

*Heterogeneity* in demand implies that customers exhibit differentiated technical requirements, based on specific characteristics of their technical systems. To give an example, large airlines put enormous pressure on aircraft manufacturers to develop new designs or versions of a basic design in order to fit their route structure economically. In turn, aircraft manufacturers systematically ask engine suppliers to commit to product configurations that fit efficiently their airframe structures.

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 is ruled out.

The effects of heterogeneity is magnified by the presence of *non-linearity* in the underlying technology. Non-linearity implies that it is almost impossible to decompose the design task in such a way that specific requirements can be pursued without the need to redesign the entire product.

Recent works on the economics of decomposition of large systems (Birchenhall et al., 1998; Frenken et al., 1998) show, using evolutionary models, that if the decomposability is low, then agents should search across the whole design space in order to find optimal solutions. This makes the finding of the optimal technical solution harder (less probable), while acceptable local optima are represented by multiple points in the design landscape.

As it is well known, non linearity implies that the solution of large engineering problems (i.e. the aerodynamic configuration of a wing) depends very much on initial conditions. Designers develop the attitude to work on the neighbourhood of existing solutions, because this preserves the accumulated knowledge. This applies equally to that particular type of engineering knowledge called system integration.

This characteristics can be seen as the result of the ruggedness of the landscape of technical parameters (Kauffman, 1993; 1995, pp. 279-298). Since product performance depends, often in a non-linear way, on a large number of very specialised sub-systems and components, and the interaction gives origin to strong complementarity effects, there may be many possible solutions to design problems, which correspond to local maxima in a landscape. This is true even under a dominant design situation at the level of product architecture. Each customer may pursue a idiosyncratic avenue to the integration of the complex system, asking suppliers to invest in application-specific solutions.

Given "multiple equilibria" in the design landscape the specific path followed by each form is heavily dependent on specific requirement of users. Given the idiosyncratic nature of engineering system integration, this learning is likely to be context-specific.

Windrum and Birchenall (1998) recently showed that the emergence of dominant design is only a special result of technological competition. The existence of heterogeneous users may even lead to the presence of alternative designs within a niche.

In sum, dealing with heterogeneous users involves learning different regions of the design space. We call this effect "learning form heterogeneity".

Furthermore, market demand may be highly *discontinuous*. For example, in production-on-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. Gaining the contract in the bidding stage is of paramount importance for suppliers, since there may be no market alternative in the short term. This has two implications. Firms have the tendency to compete through the price, by quoting a price below average costs and trying to recover the profitability during the life cycle of the contract (for example, through engineering modifications, additional works, or maintenance and spare parts). Therefore, these industries exhibit *both* fierce price competition and non-price competition based on product differentiation and technological supremacy. Second, demand volumes cannot be increased through reductions in price after the contract is awarded. Demand is completely rigid to price after the award stage. 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 loosing several bids in sequence. The cost of error may be simply too high.

There is another important effect. Discontinuity of demand prevents any single producer to monopolise the industry (Bonaccorsi, 1996). In fact, discontinuity implies that aggregate demand dynamics is irregular and badly behaved, so that long term correct forecasting is impossible. Under these conditions, planning of production capacity is likely to generate cobweb phenomena, with associated peaks of demand and large backlog in orders. Customers would never support a monopolistic industry, which might expose them to scarcity and/or very long delays in delivery.

Finally, in these industries market demand cannot be addressed without making heavy investments into *relational* activities. Users influence design, development, production and post-production (maintenance, up-grading) activities of suppliers to a considerable extent. Supplier-user relations in involve reciprocal investment in the relationship, strong technical cooperation during the design phase, high costs of development, 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 of continuous feedback.

Heterogeneity, discontinuity and relational intensity are clearly relevant features of demand, which are shared by many important industries. Together with the de-coupling between product and process innovation, these features are responsible for the departure of industry life cycle from the pattern predicted by the theory.

Let us illustrate a detailed industry case study which shows several anomalies.

## 3. Aircraft-engine industry life cycle

This section presents a brief history of the commercial aircraft engine industry from the introduction of the turbojet (1958) to date. The focus is on the technological evolution and industry structural dynamics. On one hand, the nature of technical uncertainty, the drivers of technical advancements and the rate of new product introduction are examined, while the industry level is analysed in terms of patterns of entry and exit and market stability (level of industry concentration, instability of market shares, turbulence of players' positions)[1].

Changes in technological and market uncertainty determine the unfolding of differentiated patterns of industrial evolution over the life cycle. Based on major entry events three different stages can be identified: 1958-1966, 1967-1980 and 1981-1997. The analysis of the industry evolution within the three stages is preceded by an examination of the period of early introduction of the jet for military applications.

Tables 3-4 and figures 1-2 summarise measures of entry and exit, introduction of products, level of industrial concentration, entry and incumbent market shares instability and transition matrices over the rank across the three stages.

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[1] Measures of market stability are presented in Appendix 1.

We use different sources of data to reconstruct the entire life cycle of the industry, precisely *Atlas Aviation* and *Jane's All the World Aircraft* databases and some literature on the history and technological development of the aviation industry[2]. *Atlas Aviation Database* contains all the transactions occurring from 1953 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. *Jane's All the World Aircraft* 1940-1960 is used to reconstruct the engine industry since the first introduction of the jet technology in military aviation.

## 3.1 The evolution of technology and industry

### *3.1.1 Early introduction of the jet technology*

From the beginning of the powered aircraft industry until Second World War, the propeller-piston engine combination was the prominent aircraft propulsion system. From 1910 to 1945 the development of *piston* engine technology allowed important improvements in many dimensions. Difficulties encountered in further developing piston engines induced the search for alternative forms of propulsion systems, ranging from different forms of piston engines, to gas-turbine driven turboprop and turbojet powered systems (Constant, 1980).

The technological improvement of the piston engine generated technological knowledge and experience which proved useful for developing alternative forms of power. During the 1930s the revolutionary development in aircraft structure (from wood and cloth to metal construction) created a new fertile environment for the birth of the turbojet. Many other innovations in airframes (retractable landing gear, leading edge-slots, Fowler flaps, techniques of control-surface balancing and structural prevention of control-surface reversal) and in piston engines (fuel pumps, fuel lines and sealants, lubricants, electrical and control systems, insulating materials) were also necessary to the jet.

The search for alternative forms of propulsion systems was driven by the military need to operate at higher altitude and speed. 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*, using an internal combustion gas turbine to drive a conventional propeller, and *turbojet*, using an internal combustion gas turbine as gas generator and a reaction

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[2] 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; Vincenti, 1990; Norris and Wagner, 1997, Sutton, 1998.

propulsion nozzle as thrust producer. Each propulsion system was designed for specific operating conditions (aircraft speed, altitude, air density and temperature, passenger capacity).

The war sped up the development of the jet engine. 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).

The emergence of the new technology created the opportunity for entry of new companies in the engine industry, while many of the piston engine manufacturers began to develop jet engines for military application. This period was very fertile for the introduction of new product designs and for the entry of new companies into the infant jet engine industry. Table 1 shows the composition of the industry in the period 1940-1955. The number of piston engine manufacturers decreased from 1940 to 1955, while soon after the war 12 companies were developing and producing jet engines. Their number increased to 26 in 1955.

Many efforts were made to apply the gas turbine engines to airliners. Engines efficient enough to power airliners were at the beginning the result of the military desire to get long-range jet bombers and faster fighters. “Military buyers were especially welcome to engine manufacturers for their willingness to take bigger risks than commercial buyers in developing new engines” (Miller and Sawers, 1968). Once manufacturers learnt to design big and efficient jet engines at military expense, they could become able to produce new projects to meet commercial requirements.

Table 2 shows the number of engine manufacturers distinguished by the engine technology adopted. 16 out of the 26 companies that developed and produced jet military engines during the period 1940-1955, were also supplying engines for the commercial market. 6 large piston manufacturers did not adopt the new technology and 10 new companies entered the jet engine industry. It is reasonable to suppose that the set of firms with the commercial capability to produce jet engines comprised 9 companies (second line of the table)[3]. They could potentially enter the market for jet airliners, by joining the technical knowledge cumulated for the development of the turbojet engine with the previous experience of production for the commercial market.

However, few companies assumed the risk to develop 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. The first jet engines powered conventional airframes, which were previously powered by piston engines. After the war airframes were unsuited for the new performances and functionality that the jet

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[3] Immense capital and R&D investments provided a natural barrier to entry for firms completely new to this industry.

technology could offer. Therefore, a long period of co-evolution of engine and aircraft design followed. While the turbine engines were mechanically simple, integrating the process of turbojet operation was very complex and involved the redesign of many aircraft subsystems.

The technical problems to be solved concerned the size of the aircraft, the position of the engines, the high fuel consumption, the durability. All these problems had not been revealed by military experience[4]. This stage of technological co-evolution was subject to substantial fundamental uncertainty on the scientific rules underlying the integration of engine and airframe.

The resolution of 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 procedures and facilities. Testing was especially important for commercial applications. A civil engine needed to be tested longer than a military engine, and the test had to be aimed more at reliability and durability[5].

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 requirement economically. Costs and performance could not be accurately evaluated ex-ante, while the adoption of the new system implied a new set of criteria to evaluate technology. Exhaustive attempts had to be made which increased the cost.

The question was probably more commercial than technical: companies were facing the uncertain perspective on the real economic applicability of the technology. At the same time they were facing the high costs of developing such a complex system, to be recovered on the commercial market. The uncertainty of the airline companies was also determinant for the decision to develop a new engine for the commercial market (Sutton, 1998). The size of the launch orders was determinant for the entry decisions of aircraft and engine manufacturers.

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[4] “The dominant note in military aviation is performance. The dominant note in civil aviation is, or should be, economy. The answer to both these needs lies predominantly in matching the most suitable power plant to the most efficient airframe for the job. And, because, in the present state of the art, extremes of performance and economy are not compatible, a gulf is emerging between the lines of evolution of the military and civil aeroplanes” (*Janes All the World Aircraft*, 1948).

[5] If the engine is developed for both military and civilian, the two versions go to the tests required for the civil version.

**Table 1. Number of firms in piston and gas turbine engine industry - 1940-1955**

| ***Year*** | **1940** | **1945** | **1950** | **1955** |
|---|---|---|---|---|
| ***Piston*** | 89 | 58 | 35 | 19 |
| ***Piston**** | 22 | 23 | 11 | 12 |
| ***Gas Turbine*** | - | 12 | 24 | 26 |

Source: Elaboration based on *Janes All the World Aircraft* 1940-1955 publications.
*Larger piston engine manufacturers selected on the basis of the number of products introduced.

**Table 2. Potential entry**

| **Period 1940-1955** | | |
|---|---|---|
| Piston and Gas turbine | | 16 |
| *civil* | *9* | |
| *civil piston* | *8* | |
| *civil GT* | *4* | |
| Gas Turbine (new entry) | | 10 |
| Piston | | 61 (6*) |

*Larger piston engine manufacturers selected on the basis of the number of products introduced.

### *3.1.2 First stage: 1958-1966*

The first stage is defined by the introduction of large jetliners into the market, that marked the birth of the commercial turbojet engine industry.

The first successful new engine powering a civil aircraft was the turboprop Rolls Royce Dart applied to the Vickers Viscount which entered service in 1953. In 1954 the jet powered de Havilland Comet entered the market but it failed. It experienced more than one accident, because of technological problems probably due to the early entry into the market. In 1958 a modified version of the Comet entered the market, but 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 Sud Aviation introduced the Caravelle powered by a Rolls Royce Avon. Among the potential entrants, only Pratt & Whitney and Rolls Royce competed successfully in supplying the main airframe manufacturers.

Some companies like General Electric, the first to develop a jet engine in the US, followed a more prudent behaviour, with respect to the too-early introduction of gas turbine engines in the commercial market (Miller and Sawers, 1968), probably misjudging the potential of the civilian segment (Bluestone, Jordan and Sullivan, 1981). General Electric made an experiment in entry, by powering the unsuccessful Convair 880 and 990. Wright, which supplied thirty of the world's major airlines after the War, did not adopt the new technology because "there was little appreciation in the

Fausel, 1990). Allison decided to enter the turboprop market, probably considered less risky than the turboprop.

This period witnessed fierce competition between conventional and new systems. New jet powered aircraft provided higher speed, but costs were high for short routes. This explained the resistance of the DC-3, the introduction of turboprop aircraft to replace the DC-3 and the subsequent development of the turbofan. The cost reduction provided by the jet engine came from the ability to power larger and faster aircraft than could be built with piston engines, bringing larger savings on the longer routes. The turbojet engine was more efficient than a piston propeller engine at speeds over about 450 m.p.h. (Miller and Sawers, 1968). At medium speed and altitudes the turboprop was generally more efficient than a pure turbojet. Its main disadvantage was that it carried with it all the weight and complexities of mechanical characteristics of any propeller system.

Further design innovations in the turbojet, such as the turbofan, provided much greater propulsive efficiency and supersonic performance[6]. The first turbofan engine was the Conway, introduced by Rolls Royce in 1960. The success of Conway induced the competitor Pratt & Whitney to adopt the turbofan, that emerged as the dominant design.

In this stage few engine programs and versions were introduced (tab. 3). The first programs were previously developed for military use. The variety of the solution proposed was low, because given limitation of resources and time, the undertaking of different new design programs was practically impossible.

Technical and market uncertainty explained above had three important effects:

- delay in the introduction of the turbojet for civil applications (about 15 years after the establishment in military aviation);
- reduced entry into the market (only two companies, Pratt & Whitney and Rolls Royce, developed successfully turbojet engines for airliners);
- low variety in the design solutions.

The industry structure was characterised by a *stable duopoly* dominated by Pratt & Whitney. The level of concentration was clearly high (fig. 1). Industry stability is shown by the low Pashigian index of market share instability (fig. 2) and by the invariance of the players position as indicated by the presence of 1 on the diagonal of the matrix in table 4.

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[6] The turbofan (ducted fan or by-pass engine) is a variant of the turbojet which combines qualities of pure turbojet and turboprop. It increases mass flows and reduces exhaust velocity, thereby raising propulsive efficiency at moderate speed.

**Table 3. Entry and product introductions**

| | ENGINE | | | AIRCRAFT | | |
|---|---|---|---|---|---|---|
| | **1958-1966** | **1967-1980** | **1981-1997** | **1958-1966** | **1967-1980** | **1981-1997** |
| N° of manufacturers | 2 | 4 | 9 | 5 | 10 | 9 |
| Entry | 2 | 2 | 5 | 5 | 5 | 3 |
| Exit | - | - | - | - | 3 | 3 |
| N° of programs | 7 | 13 | 17 | 8 | 19 | 30 |
| N° of programs - average | 0,78 | 0,93 | 1,00 | 0,89 | 1,36 | 1,76 |
| N° of new programs | 6 | 6 | 10 | 8 | 11 | 17 |
| N° of models | 8 | 25 | 35 | 21 | 65 | 70 |
| N° of models - average | 0,89 | 1,79 | 2,06 | 2,33 | 4,64 | 4,12 |
| N° of new models | 8 | 20 | 15 | 21 | 52 | 42 |
| N° of versions | 19 | 54 | 103 | 55 | 128 | 113 |
| N° of versions - average | 2,11 | 3,86 | 6,06 | 6,11 | 9,14 | 6,65 |
| N° of new versions | 19 | 44 | 71 | 53 | 102 | 70 |

**Figure 1. Industrial concentration**

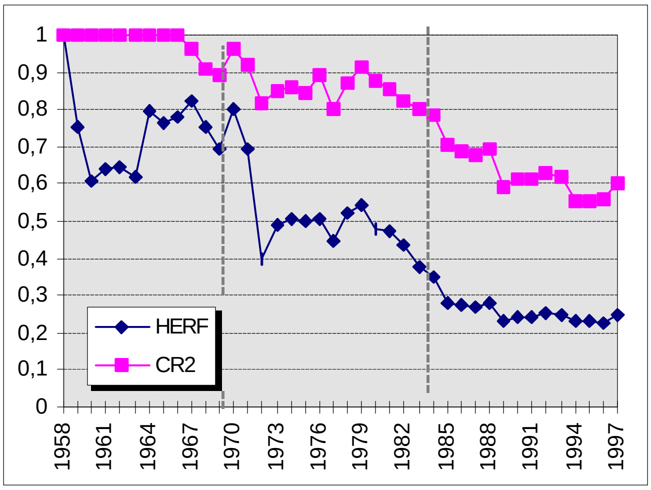

**Figure 2. Market share instability by entrants and by incumbents**

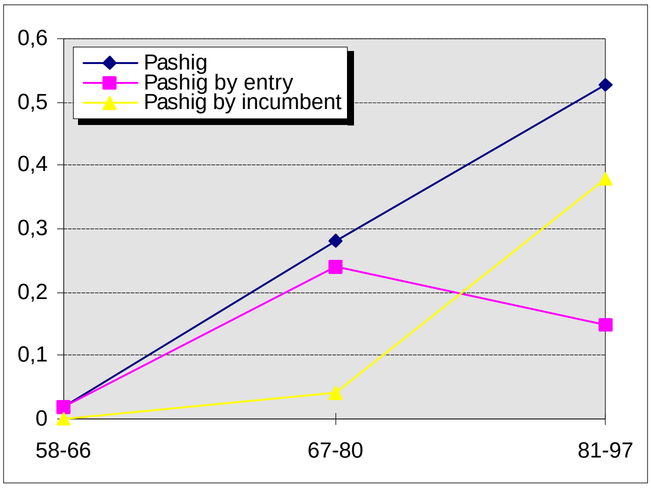

**Table 4. Turbulence of the players' position**

**1958-1966**

| | **#1** | **#2** | **>2** |
|---|---|---|---|
| **#1** | *1* | 0 | 0 |
| **#2** | 0 | *1* | 0 |
| **entry** | 0 | 0 | *0* |

**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* |

### *3.1.3 Second stage: 1967-1980*

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

The growth of market orders started in 1964 represented a message about the reduction of demand uncertainty and created opportunities for entry. The total number of orders increased from 1964 to 1968 at an average yearly rate of 59 per cent.

On the technological side this stage was characterised by technological advances in different fields. The by pass ratio (BPR) increased enormously with respect to the first jet introduced. General Electric developed a military engine with a BPR of 8:1, which was subsequently used for civil purposes (Norris and Wagner, 1997). The number of engines shifted from 4 to 2. It was more clear that the twin engine capabilities exceeded the three or four engines they replaced in terms of fuel savings and increased payload (Bethune, 1994). During the 1970s new requirements drove the process of technological innovation: safety, reliability, durability and eventually environmental factors like reduction of noise and pollution.

This stage witnessed the birth and development of new market segments for the turbojet engine technology. First, by the middle of the 1960s, the jet powered aircraft was the most efficient for routes over about 200 miles and for passenger capacity of more than about 50 passengers. Below these parameters the turboprop was more efficient, with its advantage coming from the greater efficiency of the propeller at low speeds and for take-off. The continuous improvement in the efficiency of the jet engine lowered the range and size at which the jet could compete with the turboprop (Schaffler, 1991).

Second, the big fan engines and the wide-body aircraft such as the B747 came into the market.

Technological innovation and birth of new segments contributed to a growing product variety. The growth of the number of programs, models and versions was evident with respect to the first period (tab. 3). This is only partially due to the entry of new actors, which introduced only two programs and few variants.

A major change occurred at the design level, precisely the increasing interchangeability of engines on newer model aircraft (Bluestone et al., 1981). Airframes started to be built to accept anyone of several turbine configuration offered. This trend lead to the shift from single to dual and multiple sourcing strategies of aircraft manufacturers. While at the beginning aircraft makers tended to operate in single sourcing, or in some cases in dual sourcing for specific aircraft models, the solution of major technical problems during the first stage of industry evolution, while reducing the degree of uncertainty, allowed at designing aircraft to integrate different engine configurations. Multiple sourcing policies began to be adopted at the aircraft program level. This played a key role for the emergence of General Electric as a turbojet power. Major engine companies attempted to enlarge their market by supplying different users, especially all big aircraft manufacturers (Boeing, Douglas and the new entrant Airbus)[7].

Companies began to develop families of product designs, based on the concept of "robust Rothwell and Gardiner, 1989, 1990). Robustness occurred in terms of adaptability of the basic design to different customers and to different market segments. It allowed some degree of economies of scale and scope on the production side and offered the possibility of enhanced learning from user experience. In fact users, working with similar platforms, could be more apt to ask for specific modifications of design.

At this stage, the industry moves form a duopolistic to an oligopolistic structure characterised by intense rivalry. Engine manufacturers compete in terms of customers and new products. They strive to get into the market with launch engines for new aircraft.

The level of concentration decreases because of the entry of new large competitors (fig. 1). Entry also caused mobility of market shares (fig. 2). The increase in industry instability is also shown by the change in the players' positions: the leader maintain its position, while entrants destabilise the second player position (tab. 4).

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[7] Some scholars analysed pros and cons of sole, dual and multiple sourcing (Bailey and Falmer, 1982; Demski et al., 1987; Riordan and Sappington, 1989; Richardson, 1993). In the aircraft industry alternative sourcing provided advantages through the development of competition among suppliers, gave better information about suppliers' cost and performance capabilities and increased the opportunity for innovation. It also created an insurance policy for cases of demand peaks, particularly important in an industry characterised by discontinuous demand.

### *3.1.4 Third stage: 1981-1997*

By the 1980s the third jet-age re-equipment cycle was under way. Noise and pollution regulations, fluctuating fuel prices and airline deregulation are the determinants of the technical and market evolution in this stage.

High by-pass ratios enabled lower noise levels, and by the 1980s they become available also for short and medium range aircraft (Gallois, 1994). Developments in engine testing were carried out to extend the engine life time, while conforming to the standards of safety and airworthiness (Dawson, 1984). ETOPS (extended twin engined operations) has become increasingly important to reduce airlines' operating costs and to give passengers more direct routes and shorter travel times (Bethune, 1994).

Advances in the nacelle technologies, research in new materials and in digital engine controls are the current technological challenges to improve power, safety, cost and environmental aspects related to the power systems (Select Committee on The European Communities, 1989; Williams, 1991; Farman and Joby, 1994; Goulette, 1995; Nield, 1994; Todd, 1994).

The development of the UDF (Unducted Fan), or ultra by-pass engine, promises roughly the same speed as a conventional turbofan, but with large fuel savings (Hayward, 1986).

Technology seems to be a major driver of the competition. The rate of introduction of new products and versions is very high, and, as in the previous stage, it is not determined by entry.

Post-sales support in terms of ease of service, product reliability, parts availability and long run minimisation of operating costs, is also an increasingly important competitive factor (Walker 1996; Doyle, 1997; Seidenmann, 1998; Warwick, 1998). Once major engine manufacturers supply the largest aircraft producers, they become increasingly geared toward marketing to airlines rather than only to airframe manufacturers.

At this stage we still observe an oligopolistic industry characterised by the presence of an intense competition among four large players and by minor entries that do not destabilise the industry. The level of concentration decreases and tend to stabilise to a relative low level (fig. 1). Market share instability assumes a very high level, but, unlike the previous stage, it is determined by competition among incumbents (fig. 2). Table 4 confirms this pattern showing the high level of turbulence of the rank. The leader loses its position and the mobility is high at all levels.

## 3.2 Anomalies in the jet engine industry

Our data show significant variations with respect to the events predicted by life cycle models. In particular, we observe that:

- the initial stage of the industry is characterised by limited entry: while at least nine companies share the technological capabilities to develop a commercial jet engine, having gained significant experience in military jet programmes during the Second World War, only two (Pratt & Whitney, Rolls Royce) bet on the civil application of the technology;
- the initial developments of product design are very limited in terms of alternative solutions in the design space;
- the emergence of dominant design is not followed by a shake-out of the industry, bur rather, due to the reduction in technological and market uncertainty, by the entry of new large competitors (General Electric, Snecma);
- the final stage of industry life is characterised by the stabilisation in the total number of incumbents, as predicted by the theory; however, market shares are subject to wild fluctuations over time, against the predictions of the theory.

In sum, the birth of the industry is not associated to high variance in product designs and to significant entry; the dominant design stage is not associated to exit, but rather to entry, the maturity stage is not characterised by stability but rather by extreme turbulence.

These anomalies raise interesting theoretical and empirical questions, which we explore in the following sections.

## 4. Network dynamics and evolution of the industry

In order to explore possible reasons for these anomalies, we apply a new methodology, illustrated and developed for the first time in a companion paper (Bonaccorsi and Giuri, 1999). We study two industries simultaneously, which are vertically related via exchange of products.

In order to fully capture the joint effects of technology and market demand on industrial dynamics, we use the notion of network. In our meaning, a network is an input-output matrix whose cells contain exchange values between *individual* firms operating in two vertically related industries. According to the terminology introduced in Bonaccorsi and Giuri (1999), a A-matrix is a biadjacency matrix of a bipartite graph with binary values (i.e. an exchange exist/does not exist). In this paper we use measures of A-matrices for each year of the life cycle of the industry based on individual data on transactions between aeroengine manufacturers and aircraft producers.

The structure of the network at the beginning and at the year of transition among stages is shown in figure 3. 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.

Network dynamics is represented by measures of relational density and of engine group centralisation for each year of the periods, that are computed separately for the entire network and for the core.

At the company level we analyse the dynamics of the actor degree and of the actor centrality.

A key result of the analysis is that network measures closely follow the transition across stages[8].

Changes in the network structure are interpreted as indicators of changes in the underlying determinants of industry life cycle and provide an explanation of the anomalies detected.

In addition, we try to relate network measures to industry measures, in order to identify the effects of network dynamics on industry evolution. In particular, we explore the relationship between density and concentration at the industry level and between actor centrality and market share at the actor level in the three stages of the industry life cycle. We interpret the results as indicators of transitions in the structure of the underlying network and of the industry. The results show that the relation between network measures and industry measures carefully signals changes in industry life cycle.

## 4.1 First stage (1959-1966): fundamental uncertainty and network creation

ILC theories assume that the initial stage of a technological trajectory is characterised by high uncertainty over design parameters. Firms explore many alternative configurations of products, that is, many regions in the landscape of fitness which depends on combinations of design parameters. Consequently, the initial stage is characterised by massive entry and a large variety of products in the market.

This characterisation of technological uncertainty is correct, but not general. In the case under analysis, two factors must be considered, which lead to entirely different implications in terms of industry life cycle.

First, the birth of jet technology was dominated by a *fundamental type of uncertainty* (i.e. will a large transport plane with such an engine ever fly? will the experience gained by developing military jet aircraft be applicable to large transport jet aircraft?), coupled with very high *costs* of development and testing. This type of fundamental uncertainty can be reduced only by producing a demonstration of feasibility, which, in turn, requires maximum concentration of effort on the realisation of prototypes. The resolution of uncertainty did not require the exploration of many independent alternatives, but rather the tight coordination of many scientific and technical competences over a few basic designs. In general terms, consideration of development costs *mediates* the relationship

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[8] Network measures are presented in Appendix 2.

between technological uncertainty and the extent of entry. A strong trade-off between efficiency and variety may be in place (see for a similar point, Foray and Conesa 1995).

Second, models of ILC usually relate to new classes of products that are not greatly dependent for their functioning on other products, as it is the case for consumer goods or standard capital goods. The test of the properties of these products can be performed by producers in relative isolation from users. This is not the case for complex intermediate products which must fit to other technologically complex products. These products are *nested* into large systems and their performance can be tested only by direct interaction with manufacturers of the systems. Here we find a case in which *learning by interacting* requires physical interconnection. Therefore, the resolution of uncertainty required the interaction with customers for the testing of a few basic configurations.

In turn, the fundamental nature of uncertainty meant that customers did not have any incentive to explore a variety of solutions, but rather worked closely with a single engine supplier in order to figure out the viable configuration. This required heavy relational investments, in terms of dedicated personnel and instrumentation, and idiosyncratic, relational learning trajectory. There was no significant learning from variety (learning from heterogeneous suppliers).

The combination of fundamental uncertainty and relational learning explains the structure of the network at stage 1.

In 1958-59 two suppliers created a partitioned network. PW and RR supplied aircraft manufacturers within close and stable relations. Relations were mainly one-to one on the part of the users, that operated in single sourcing (fig. 3, year 1959 and 1966).

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 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.

Network dynamics is evident by looking at the density (fig. 4), which was at the highest level at stage 1[9]. During the following years the level of density first decreased because of new entrants, and then stabilised at a quite high level.

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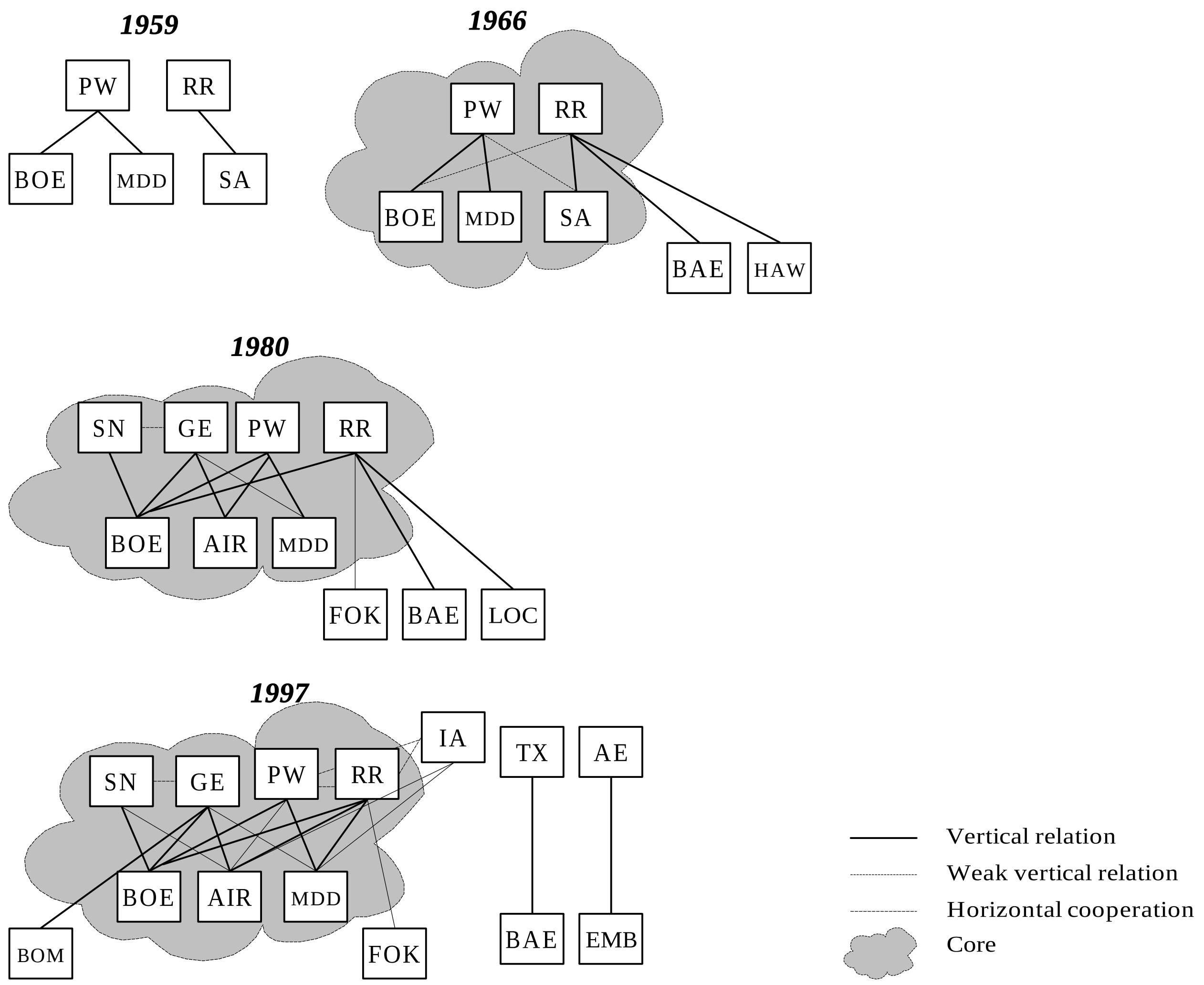
[9] Measures in the first stage are more dependent on the small number of actors. Precisely, indexes present a higher range of variation, because a single relation has a higher weight if the total number of relations is low. This is not a problem for our analysis, because network indicators embody information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

In the core of the network the density was also close to the maximum value (fig. 4). 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 (fig. 6).

Few actors entered the industry at this stage. *It is the structure of the network, rather than the size of the market, which explains the limited amount of entry*. Given that customers preferred exclusive relations, there was no room for further entry, once the network crystallised. Also, the existence of a small number of aircraft manufacturers determined a restricted space for subsequent entry, given the preference towards single sourcing strategies, and the high investments in specific relations.

The dynamics of the network at stage 1 also influenced the development of technology. A dominant design emerged in the configuration engine-aircraft, as the result of the solution of system integration uncertainty. 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. But again, entry was influenced by the structure of network.

**Figure 3. Network structure in 1959-1966-1980-1997**[10]



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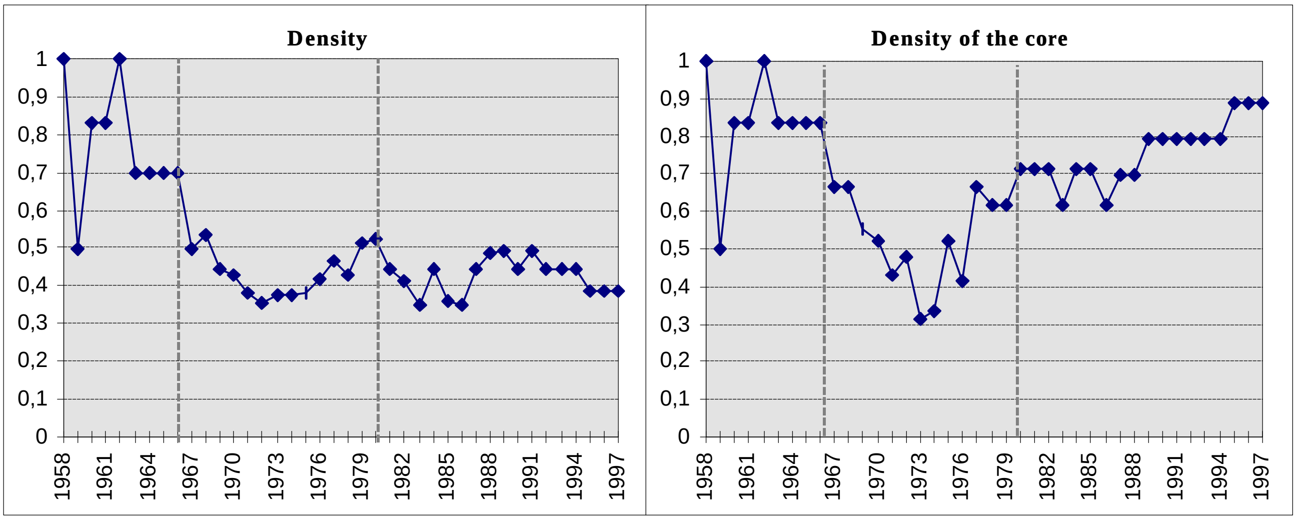
[10] Company names are reported in Appendix 3.

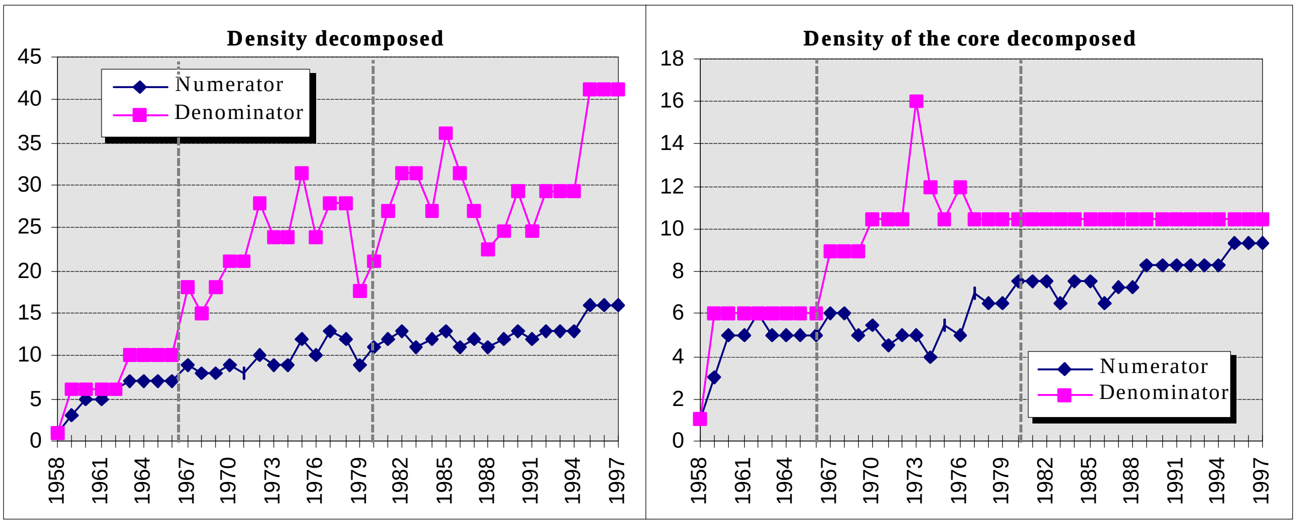
**Fig. 4 Relational density**



Density

Density of the core

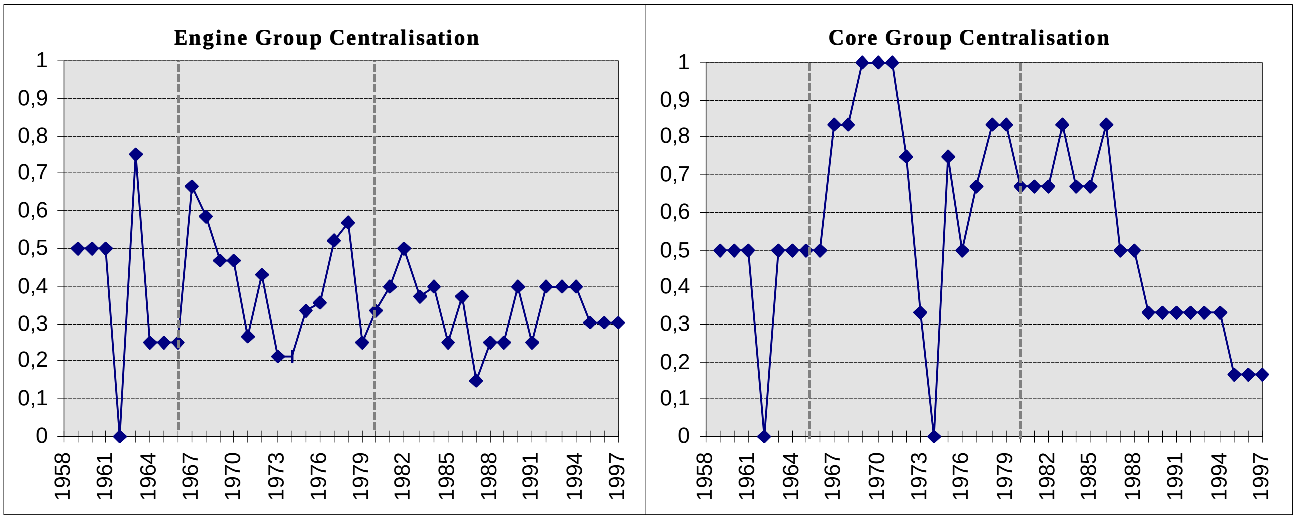
**Fig. 5 Relational density decomposed**



Density decomposed

Density of the core decomposed

**Fig. 6 Engine Group Centralisation**



Engine Group Centralisation

Core Group Centralisation

## 4.2 Second stage (1967-1980): learning from heterogeneity and network diffusion

At stage 2 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 at 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 the interest to open relations with many engine suppliers, exploiting different technical capabilities. Here a strong effect of *learning from heterogeneity* can be found.

At stage 2 the network changed completely its structure (fig. 3, year 1980). Other aircraft manufacturers and two large engine suppliers (General Electric and Snecma) entered the industry. Entry was stimulated not only by the growth of the market size, in terms of total orders, but room for entry was created by the adoption of multiple sourcing strategies by aircraft manufacturers. In fact, entry did not occur to fill uncovered niches of the market, but to compete directly with incumbents in existing and new market segments.

The evolution of the network was characterised by diffusion of relations. Each customer looked for supply relations with more than one engine manufacturers and opened new relations. Again, the dynamics of network reflects the evolution of underlying technology.

The decomposition of density at stage 2 (fig. 5) shows an interesting pattern. 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 with respect to the first period due to entry, from 1967 until 1972; after that period the relational activity leads to a further increase in density (fig. 4). Within the core, the dynamics was similar but the number of new relations opened by central actors increases more rapidly, so that density kept high.

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.

At stage 2 the structure of the network allowed all engine suppliers to get access to central customers. Initially, the entry of new suppliers reduces the density. Progressively, however, policies of multiple sourcing on the part of aircraft manufacturers multiply the number of relations and increase the density of the network again. This means that at the end of stage 2 all actors had mutual access to each other, particularly in the core, in which density was as high as 0.7 (fig. 4). How does the network dynamics at stage 2 influence the evolution of technology in the last stage of industry life?

Given the importance of learning from heterogeneity at this stage, all major engine suppliers 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 stabilisation effect on the network. On the other side, technological innovations could rapidly be available to all aircraft manufacturers.

### 4.3 Third stage (1980-1997): equalisation of opportunities and network stabilisation

Once engine manufacturers gained a structural position of access to all major aircraft manufacturers, the focus of competition shifted over the second layer of the vertical network, represented by the airline companies. Therefore, the dynamics of quantities associated to each relation was determined by two factors: first, by technological advancements 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.

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 a 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 it is clear from the decomposition of density, the number of possible relations in the core stabilised and remained unchanged over a 15-year period (fig. 5). The high density of the core acted as a barrier to entry for engine manufacturers.

Opportunities to entry were available only to joint ventures with established actors (as in the case of International Aeroengines) or to companies which targeted a specific application for aircraft manufacturers positioned at the periphery of the network (as in the case of Allison, supplying Embraer, and Textron, supplying Bae). JAE, MTU and Fiat enter directly the core through the International Aeroengine cooperation, dominated by Pratt & Whitney and Rolls Royce.

While the density of the network still declined, although slowly, due to entries (fig. 4), the density of the core sharply increased and stabilised over the levels which were typical of stage 1. This means that the network assumed a 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 a few relations and mainly with non-core actors.

The structure of network also explains the surprising finding that, at stage 3 and still today, market shares exhibit remarkable turbulence. In fact, the centralisation of core actors declines and finally stabilises over a very low level (see figure 6). Although the core becomes more and more stable in terms of number of actors and relations, no central actors dominates over the others in terms of structural position. This remark also applies to the whole network. The relational equivalence of central actors explains the instability in market shares and the turbulence of the players' positions. Because no engine supplier is excluded from market opportunities (i.e. new aircraft programs), there are not established leaders in the core. Therefore, depending on fluctuations of customer demand, market positions change in a turbulent way. This suggest a somewhat different picture of a maturity stage in industry life cycle than the picture portrayed by established theories.

Instead of standardisation of technology leading to the emergence of dominant leaders based on economies of scale, there is still heterogeneity in technical solutions. However all customers in the network have access to all suppliers and viceversa. 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 is 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 shake-out of the industry, the final stage shows the persistence of several competitors which fiercely fight each other.

Finally, exit of suppliers does not occur during all the period. The presence of high switching costs for aircraft and airlines companies, and the stable relational position created by suppliers reduce the probability of companies to leave the industry.

### 4.4 Relation between network and industry measures

In a previous paper we showed that the analysis of the sign of the relation between density of the network and concentration of the industry provides useful information on the underlying technological and industrial regime (Bonaccorsi and Giuri, 1999). To make predictions on the sign of this relation some substantive assumptions must be made regarding the process underlying the creation of linkages in the A matrix and the distribution of quantities exchanged in the $B_i$ matrices. Assumptions are based on three important factors.

First, the magnitude of the perturbation induced by the new relation. In some industries a new relation requires high transaction-specific investments due to dedicated technologies and human capital, experimentation and testing procedures and facilities. In other cases the discontinuous nature of demand creates a threshold in the market and a relational barrier to entry. This often implies a high value of the quantity associated to the new relation. If the perturbation is sufficiently large, then the sign may be positive.

Second the probability to create new links can be uniform for all actors, normally distributed or, on the contrary, it can be asymmetric. Assumptions of uniformity can be associated to Schumpeterian I regimes. In the latter case we may assume that the higher the number of relations enjoyed by an actor, the higher his probability to create new links. If this is the case, the increase in density of relations may be associated to an increase in concentration. The asymmetric case is characteristics of oligopolistic industries. “Success breeds success” phenomena, reputation effects, source loyalty on the part of the customers and effects of learning from different users may explain why more central companies have a higher probability to create new links.

Third, asymmetry may be assumed in the distributions of losses to existing relations that favours the companies with higher market shares or with a higher centrality. In other words, the share of loss is inversely proportional to the number of existing relations or to the market share. This assumption is also consistent with Schumpeter II regimes and again, the result would be an increase in concentration.

Interestingly, the relation is negative if the *perturbation* induced by the new relation (i.e. the quantity lost by other relations) is small with respect to market size or average quantity exchanged. These conditions approximate the dynamics of a competitive market, in which relational activity of supplier firms is not sufficiently strong to induce concentration in market shares. On the contrary, the higher the dynamism in opening new relations, the lower the resulting concentration.

At the company level, given a lower bound on quantities, the addition of new relations also means that total quantities increase with respect to competition. Hence, market shares increase. Therefore we expect a positive relation between changes in centrality and dynamics of market shares.

Suppliers at the periphery are mainly single-client, and their market shares are more unstable, because of the marked dependence on fluctuations of orders of individual downstream users. In this case we do not expect a significant relation between actor centrality and market shares.

These general relations apply to the whole life of an industry and make clear the dominant factors of industrial dynamics.

We simply show the scatter diagram of the time series of network and industry measures and demonstrate that within the life cycle of an industry there may be stages in which the *sign* of the relation is different. Therefore the use of network measures may be a useful test of the life cycle periodisation.

### *4.4.1 1st stage: no relation between density and concentration; positive and weak relation between centrality and market shares*

During stage 1 there is no expected relation between density and concentration for the following reasons. The existence of only two suppliers means that density is influenced by even small variations in relational activity. The impact of the increase in density on concentration depends on the identity of the actor who opens new relations. The level of concentration keeps high because of the small number of actors[11]. If new relations are added by the leader than concentration increases; if on the contrary it is the follower which opens new relations, the opposite is true.

The quantity associated to initial relations determines market shares of the two companies. The size of the market (USA for Pratt & Whitney and Europe for RR) is considered a key determinant of the initial market share distribution.

Subsequent relations derive from weak dual sourcing: new relations are opened for specific projects, small quantities, and are short-lived and unstable. Therefore, they determine small changes in the level of concentration.

As the quantities associated to new relations are not very large (weak relations) the relation between density and concentration is positive but quite weak (fig.7). The partitioned nature of the network is maintained because of the weakness of new relations. Change in market size and distribution of losses favouring the leader explain the positive sign of the relation.

For the same reasons, at the company level the relationship is also positive but weak (fig. 8). In this case, an increase in the number of relations determines a growth in market share. However, since market shares are mainly determined by initial relations and new relations are characterised by small quantities, the increase in market share is very modest.

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[11] The minimum value of Herfindahl index with two actors is 0,5.

**Fig. 7 Relation between density and concentration**

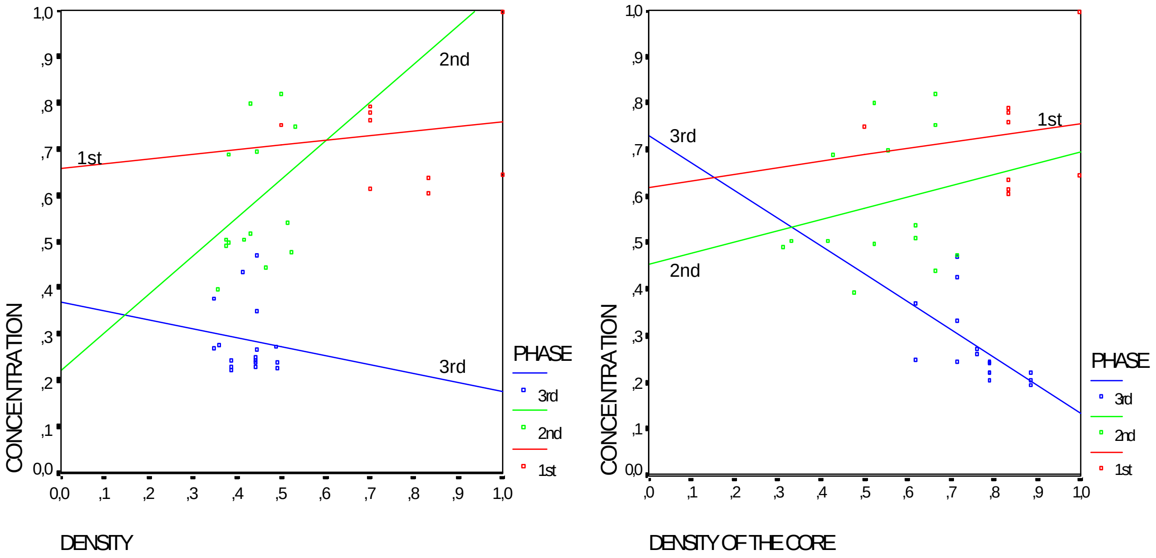
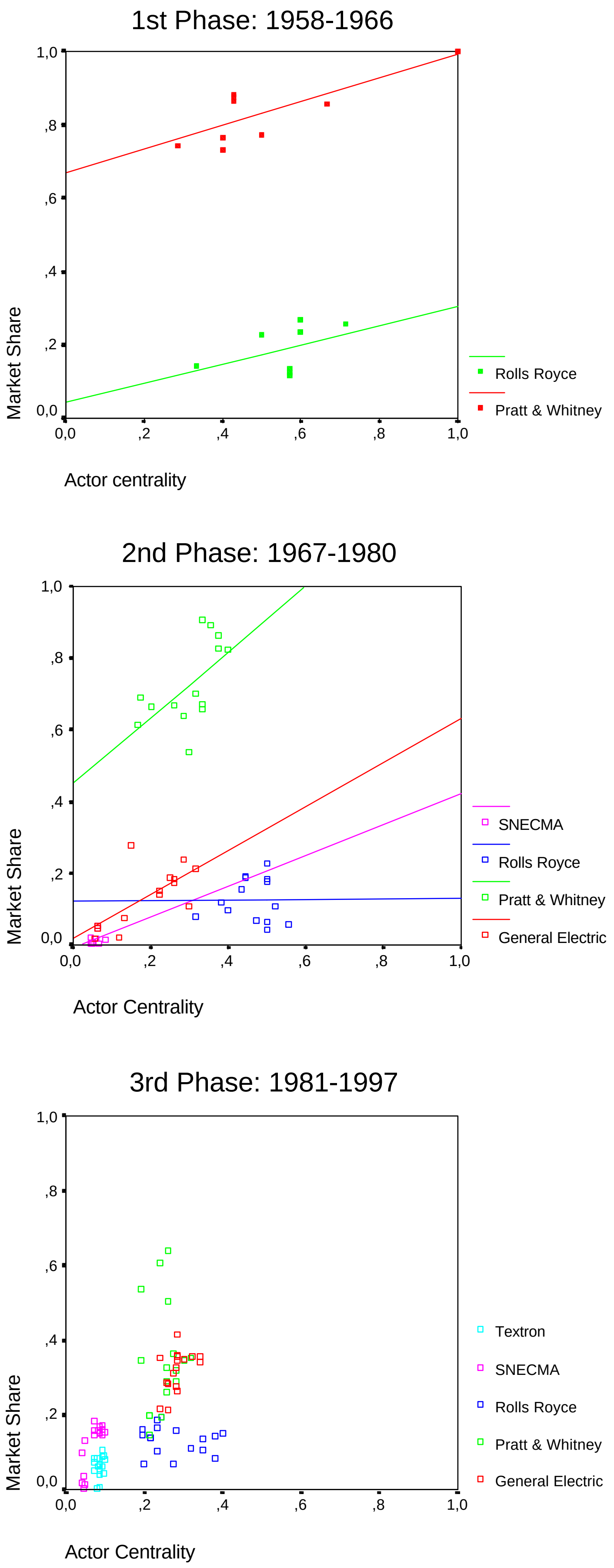


**Fig. 8 Relation between actor centrality and market shares**



### *4.4.2 2nd stage: positive relation between density and concentration; positive relation between centrality and market shares*

At this stage we observe a positive relation between density and concentration (fig. 7). This is explained by analysing separately two different phases. In the period 1967-1972 the entry of suppliers and users with a small number of relations, but large quantities associated to the relations determines a reduction in the level of density and concentration. Entry destabilises network and industry structure.

In the period 1973-80 new relations are built by incumbents (more central) as a consequence of the strategy of large customers to adopt multiple sourcing. As incumbents reduced the fundamental type of uncertainty before the new entrants, they have higher probability to increase their centrality. Given a lower bound on quantities associated to the relations, the level of concentration increases.

Consistently, at the company level the sign of the relation between centrality and market share is still positive and the relation become stronger and differentiated at company level (fig. 8). Companies adopted strategies of growth based on intense relational activity.

### *4.4.3 3rd stage: negative relation between density and concentration; no relation between centrality and market shares*

The relation between density and concentration interestingly assumes a negative sign (fig. 7). The level of density is oscillating and it is influenced by two opposite forces, both determining a reduction in the level of concentration. The positive or negative sign of the relation depends on the prevalent effect.

Given the hierarchical organisation of the network into a core and a periphery, minor entries do not destabilise the network (in terms of core and periphery) and the industry (small quantities exchanged by entrants). In fact new actors enter with a small number of relations (often only one) and the quantities associated to the relations are small. On the contrary, large incumbents create new important relations within the core.

The prevalent effect comes from the intense competition among incumbents that leads to an increase in density and a reduction of the level of concentration. Therefore we observe a negative relation between density and concentration. Interestingly, this result is characteristics of more competitive markets.

This relation is thus mainly determined by the relational dynamics within the core. We highlight this effect in fig. 7 by showing the plot of data on density of the core and concentration: in this case the negative relation is stronger.

Finally, at the company level there is no relation at all (fig. 7). Companies display a level of centrality which is roughly constant, while market shares are unstable. Companies share the same customers, and in many cases supply engines for the same aircraft program. The pattern of relations clearly shows that the third stage is characterised by a different type of competition, in which incumbents share the access to all major aircraft manufacturers. They differentiate their strategies through introduction of new technical solutions and development of network of relations with airlines by offering maintenance and after-sales services. Market shares turn out to be unstable and strongly dependent on customer fluctuations.

## 5. Conclusions

The paper develops a case history which presents significant anomalies with respect to key predictions of models of industry life cycle.

We showed how the evolution of technology and market demand is carefully reflected into changes in the structure of network, and how network dynamics explains the anomalies detected with respect to conventional industry life cycle models.

What is striking is that measures of network structure exhibit a dynamics which closely follows the time periodisation of ILC. Each stage is characterised, with reasonable precision, by different patterns in terms of density and group centralisation, both at the level of the whole network and the core. This correspondence is even more clear if we look at the *relation* between network measures and indexes of market structure.

The applicability of concepts and tools proposed in this paper is open to further research.

# Appendix 1: Market stability

### 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 for the number of engines installed in the model, as described in the technical literature.

We compute two concentration measures: the CRK and Herfindahl indexes (Grossack, 1965; Boyle, Sorensen, 1971; Curry and George, 1983).

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

$S_i$ = market share of the company $i$

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

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 highly shared among the leaders. The combination of CR2 and Herfindahl index of concentration and number of firms provides a clear specification of the supplier industry structure.

### 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; 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; Gerosky 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 the three stages 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 stage
$t-1$ = first year of the stage

The larger the value of the index, the higher is the intensity of competition. We distinguish 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 stages of industry evolution. We build transition matrices over 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* change the initial position during the period.

The three matrices assume the following form:

**$T_z$**

| | **#1** | **#2** | **>2** |
|---|---|---|---|
| **#1** | $X_{ij}$ | ... | ... |
| **#2** | ... | ... | ... |
| **entry** | ... | ... | ... |

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

$a_{ij}$ represent the number of years a firm occupying the 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.

We see if the observations are concentrated in 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 indicates companies losing positions, observations below the diagonal indicates companies gaining positions. Large values of $X_{ij}$ off the diagonal indicates high turbulence in the players positions.

## Appendix 2: Network measures

Network indicators are drawn from social network analysis contributions and adapted for the analysis of vertically related industries (Scott, 1991; Wassermann and Faust, 1994; Borgatti and Everett, 1997)[12].

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 / does not exist". Data about the number of engines exchanged are indicated in a matrix B, whose cells contain zero if the matrix A exhibits zero in the same position, and the quantity exchanged if the matrix exhibits one in that position. We use dichotomous ties (matrix A), instead of valued ties (matrix B), to compute different network indicators.

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.

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

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

The value of this index depends on the network size, that is, on the total number of actors. To allow for comparison in different years, we normalise the degree, by dividing the degree by the total number of connections occurring.

$$NCD_i = \frac{CD_i}{\sum_{i}^{E} CD_i}$$

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*, that shows the intensity of the relational activity among companies, or on the *denominator*, that 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. 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*, that is subsets of actors among whom there are relatively intense ties. In this analysis the subgroup is composed by all actors having a minimum of 2 relations for at least 5 consecutive years during the period under analysis. Actors which respond to these criteria (nodal degree and stability of the relation) are selected as members of the core during all industry life.

In this way we identify a *core* and a *periphery* of the network. The core is composed by the portion of the network whose members have ties to many others within the subgroup. On the contrary, the periphery is composed by 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.

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[12] A part of this section has been more deeply developed in Bonaccorsi and Giuri (1999).

# Appendix 3: List of companies

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

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