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Industry life cycle and the evolution of an industry network

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INDUSTRY LIFE CYCLE AND THE EVOLUTION OF AN INDUSTRY NETWORK.

The history of the commercial jet engine industry♣

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Abstract

This paper addresses the problem of the general validity of models of the industry life cycle, which have been proposed to analyse the long-term evolution of many industries, exhibiting a typical pattern of shakeout. We study a case of non shake-out in the commercial jet aero-engine industry, marked by a small number of entry events distributed over 40 years of industry evolution, by no exits and by a resulting slowly increasing number of firms. We argue that the vertical structure of the industry, as represented by the network of vertical relations between aero-engine suppliers and aircraft manufacturers, "regulated" the process of entry and exit and posed the conditions for a non shakeout to take place.

JEL classification: L13, L19, L22, L62

Key words: industry life cycle; entry, exit; network; vertical relations.

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1. Introduction

This paper addresses the problem of the general validity of models of the industry life cycle, which have been proposed to analyse the long-term evolution of many industries, exhibiting a typical pattern of shakeout. This empirical regularity stimulated many studies to detect patterns of shakeout in different industries. On the contrary non-shakeout patterns, characterising a large portion of modern manufacturing, have received less attention.

The existing literature of industrial dynamics offers several models for explaining the dynamics of industry populations. The most important models offer explanations based on a distribution of entrepreneurial talent (Jovanovic, 1982), on the impact of product and process innovation on the ability of firms to enter and compete efficiently in the market (Klepper, 1996, 1997), on characteristics of the population such as density and legitimation (Hannan and Carroll, 1992; Carroll and Hannan, 2000), on information contagion among agents (Horvath et al, 2000). All these models end up in predicting a pattern of shakeout. A non shakeout can occur when the conditions of the models are not verified.

We study a case of non shake-out in an intermediate good industry, namely the commercial jet aero-engine industry, marked by a small number of entry events distributed over 40 years of industry evolution, by no exit events and by a resulting slowly increasing number of firms. How can we explain this pattern? Why do not potential entrants enter in mass at the birth of the industry? Does the industry experience a particularly long period of legitimation? Are signals particularly weak for potential entrants? Is product innovation not so rich of opportunities to induce firms to enter the new market?

We argue that the above conditions do not explain the pattern observed in the aero-engine industry and propose an alternative explanation. We believe that the vertical structure of the industry, as represented by the network of vertical relations between aero-engine suppliers and aircraft manufacturers, “regulated” the process of entry and exit over the first 40 years of industry evolution. The vertical structure of the industry posed the conditions for a non shakeout to take place. First, by limiting the opportunities for a mass entry, second, by preventing exit. In the paper we present a qualitative explanation of the entry events, based on the analysis of the network of vertical relations.

We suggest that the notion of *network* connecting vertically-related industries takes into account both the impact of technological change and the dynamics of market demand. 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 considerations on technological learning which takes place within a single relation and from heterogeneous relations.

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 statistics on the structure of the network of vertical relations between engine suppliers and airframe manufacturers during the entire life of the commercial jet engine industry, and demonstrate that changes in technology and demand are faithfully reflected in the dynamics of the network. The analysis of the structural dynamics of the network allows us to develop an explanation for the entry and exit process.

Section 2 presents a discussion of the existing models. Section 3 develops the industry case study. In section 4, after an introduction and discussion of the network approach, we develop an explanation of entry and exit in terms of network dynamics. Section 5 offers some implications and conclusions.

2. On the evolution of industry populations

Several approaches have been developed to explain the evolution of the structure of an industry, as reflected for example in the change in the number of firms.

Jovanovic (1982) modelled the evolution of an industry in which firms learn their costs through experience, so that the probability to exit the industry because of cost inefficiency decreases with age and with size of the firm. The evolution of the industry is dependent on selection over a population of heterogeneous agents, while the assumptions on the distribution of firm types and on selection rules imply that the environment is stationary.

Several streams of empirical and theoretical work share the assumption of non stationarity of the environment in which the dynamics of industries takes place. Many industries show in fact a shakeout pattern of evolution, which stimulated several theoretical explanations.

Industry life cycles models proposed different explanations of shakeouts. The first is based on the occurrence of technological events, such as the emergence of a dominant design (Utterback and Abernathy, 1975) or an exogenous technological innovation (Jovanovic, 1994). The second explanation refers to competitive advantage for firms enjoying higher age and size, which depends on technological assumptions on product and process innovation.

In the first direction, Utterback and Abernathy (1975) and Abernathy and Utterback (1978) proposed the model as an empirical generalisation on the basis of stylised evidence regarding the *technological* evolution of industries in the long run. The initial stage of ILC is characterised by massive *entry* of new firms, while there is no advantage arising from a larger firm size. As a dominant design emerges, opportunities for exploration sharply decrease, while product standardisation allows the exploitation of economies of scale in manufacturing. The rate of entry drastically decreases, while some of the incumbents experience exit. The net result is a decrease in the number of firms.

In the second direction Gort and Klepper (1982) and Klepper and Graddy (1990) analysed empirically the pattern of entry and exit over the ILC in a number of sectors. Gort and Klepper (1982) show the number of years and the entry and exit rates in 5 stages of industry evolution, which are defined by the rates of net entry: the first stage is characterised by entry of a few firms (1 to 3), the second by a positive net entry, in the third the entry rates equal the exit rates, in the fourth the net entry rate is negative and finally in the fifth there is a stabilisation in the number of firms. Built on this work, Klepper and Graddy (1990) proposed that the number of firms follows a distinctive path in three stages: the first is marked by the growth in the number of firms, the second by a sharp decline and the third by a stabilisation. They found that many industries experienced a common pattern of shakeout during their evolution, a result which was later confirmed by Agarwal and Gort (1996) and Agarwal (1998). Recently, the predictions of the life cycle hypothesis have been replicated via a formal model (Klepper, 1996). The stages of ILC can be also naturally interpreted as transition paths from Schumpeter Mark I to Schumpeter Mark II regimes (Nelson and Winter, 1982; Malerba and Orsenigo, 1995, 1996a).

A more general framework is offered by Winter et al. (2000) within a model of industry evolution with an infinite number of new entrants. Interestingly, while some stylised properties of industry evolution (skewed size distribution, turbulence of market shares) are generated in all model specifications, the emergence of a life cycle is dependent on a particular type of model. The authors develop a specification in which firms learn only about the productivity of labour (not of capital) and generate a dynamics in which the number of firms increases monotonically and concentration decreases - i.e. there is no shakeout.

Another line of inquiry was proposed by *population ecology*. The dynamic properties of the model depends on the interplay between two processes: legitimation and competition. The former makes it difficult for organisations to establish themselves at the beginning of the industry life cycle, while the latter, on the contrary, discourages entry at later stages, when the number of incumbents, or density of the population, is large. A key prediction of the model is that entry rates will eventually fall and mortality rates will increase, so that a drop in the number of organisations (shakeout) will take place. While the predictions of the model have been substantially conformed in a number of studies (Hannan and Freeman, 1989; Hannan and Carroll, 1992; Baum and Singh, 1994; Carroll and Hannan, 1995; 2000), there are several problems with the theory. First, the meaning and operationalisation of the legitimation process are not at all clear. Second, it is possible that organisations differ in their vulnerability to legitimation, so that the dynamics and particularly the mortality rates depend on the composition of the population (Fjellstrom, 1998). Third, the dynamics depend on the consumption of a given pool of resources. Although some models allow for a change in the carrying capacity of the environment, this is not determined by the action of agents. More generally, population ecology models underestimate the adaptation capabilities of agents.

A further approach to the evolution of industry population is based on the idea that *information accumulation* leads to mass entry at the birth of an industry, which naturally leads to mass exit (Horvath et al., 2000). Mass entry is determined because at the birth of an industry firms solve the uncertainty about the profitability of entry through information accumulation on the success of incumbent firms. Once uncertainty is solved, a large number of actors enter the industry in mass, because of phenomena like information cascades, which also justify market crashes or revolutions (Caplin and Leahy, 1994). On the other hand, explanations of exit are based on efficiency reasons, that is, firms exit when their costs are higher than price. Therefore, shakeout is mainly determined by massive entry.

More generally, *coordination* problems at the birth of an industry could induce over-entry, so that the actual number of firms becomes greater than the number that the industry can support in equilibrium. Klepper and Miller (1995) test the overshooting model, built on the work of Cabral (1993) and Dixit and Shapiro (1986), which predicts declining patterns of entry and exit, in absolute and relative terms. However the predictions are not supported by data both in shakeout and in non-shakeout industries.

Coming to the empirical validity of those models, one can observe a large amount of detailed evidence. The ILC has been tested empirically in a large number of industries, which, however, share the common feature of mass production, i.e. automobile, tire, beer, penicilline, disk drive (Utterback and Suarez, 1993; Suarez and Utterback, 1995; Christensen et al., 1998; Klepper and Simons, 1997, 1999). On the contrary *non-shakeout patterns*, characterising a large portion of modern manufacturing, have not received much scrutiny. This has created a lot of debate on the general applicability of the model to other industries.

Nelson (1999) reviews several studies on long term industry evolution and calls attention to cases that do not fit into the standard industry life cycle pattern[1]. In this perspective, he argues that the ILC model does not take adequately into account the role of institutions in shaping industry structure. The model also uses a simplistic notion of technical change, as it is based on the existence of a single technological cycle. On the contrary, a number of industries have been characterised by technological discontinuities over their life cycle (Anderson and Tushman, 1990; Christensen and Rosembloom, 1995) or by gradualism and punctuation in the process of technological development (Levinthal, 1998), or finally by the emergence of distinct product niches (and designs) as a result of a process of coevolutionary learning among buyers and suppliers (Windrum and Birchenall, 1998).

While the majority of studies have analysed shakeout patterns of industry evolution, more recent attention is directed to identify cases of falsification of crucial predictions of the model (Malerba and Orsenigo, 1996b; Nelson, 1994, 1999). 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. The first group is represented by petrochemicals, disposable diapers and zippers. These industries are characterised by the emergence, after 20-30 years from the first

[1] See Mowery and Nelson (1999) for an extensive analysis of the case histories.

commercialisation of products, of specialised process engineering firms to service the needs of production plants. These firms enabled the entry of specialised manufacturing or marketing firms and eroded the advantage from plant size and process R&D of incumbents. The second group is represented by medical diagnostic imaging products. In this case, the division of labour between technical and manufacturing/marketing firms enabled the latter to enter the industry at a later stage. In the third group, including business jets and lasers, specialisation in product sub-markets stimulated over time the entry of firms differing in the mix of sub-markets served.

Commenting on Klepper's classification, Bonaccorsi and Giuri (2000a) examined departures from the ILC pattern, by identifying 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 in 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.

They 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. An example is provided by the case history of the turboprop engine industry (Bonaccorsi and Giuri, 2000a).

In the next section we describe the evolution of the commercial jet engine industry and provide a discussion of the observed patterns in the light of the existing theories. We propose an alternative explanation for entry and exit in this industry based on the dynamics of the network of vertical relations between suppliers and buyers of engines.

3. The life cycle of the commercial jet aero-engine industry

This section presents a brief history of the commercial jet aero-engine industry from the introduction of the turbojet (1958) to the present.

We use various sources of data to reconstruct the entire life cycle of the industry, specifically 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[2]. 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. The database provides data on more than 85,000 transactions, carried out by 27 aircraft companies and 11 engine manufacturers, and involving 102 aircraft models (more than 450 versions) and 260 engine types. Data on three aircraft programs not included in Atlas have been added by using Aerospatiale (1990) data on orders and deliveries. For the purpose of this study, we use data relative to the jet engine.

We integrated the *Atlas* database with data on the number of engines powering each aircraft, by using the technical press (in particular, *Flight International* and *Aviation Week and Space Technology*). *Jane's All the World Aircraft* 1940-1955 is also used to reconstruct the engine industry

[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, 1994; Vincenti, 1990; Rowe, 1993; Norris and Wagner, 1997; Sutton, 1998.

since the first introduction of the jet technology in military aviation and to identify the potential entrants into the civilian industry.

The case of jet engine has also been considered by Gort and Klepper (1982) within their 5-stage analysis of 46 product histories. They analysed the "engine, jet-propelled" industry from 1943 to 1971. Klepper and Graddy (1990) extended the data until 1981 and found the following 3-stage pattern for the jet engine industry: the number of firms increases and reaches a peak of 29 after 21 years, than decreases to 20 and finally stabilises (Table 1).

Table 1. Engine, jet propelled industry, 1943-1981

Stage	**I**	**II**	**III**
Number of years	21	8	9
mean annual change in the number of firms	1,5	-1,1	-0,2

Source: Klepper and Graddy (1990)

Agarwal and Gort (1996) further extended the time series of data until 1991 and showed for the 25 products analysed that entry and exit rates depend on the stage of industry evolution. They reprised the 5-stage evolution proposed by Gort and Klepper (1982) and discovered the following pattern for the jet engines: the mean annual rate of net entry is high in the second stage, then decreases in the fourth stage and finally stabilises (Table 2). Data for the first stage are not available while the third stage does not occur. The comparison with the mean annual entry and exit rate of all 25 products indicates that the jet engine follows the common shakeout pattern.

Table 2. Jet engine, 1943-1991

	rate of entry		**rate of exit**	
Stage	**Jet**	**mean**	**jet**	**mean**
I	-	0.39	-	0.08
II	0.20	0.21	0.03	0.05
III	-	0.06	-	0.07
IV	0.05	0.05	0.09	0.11
V	0.09	0.09	0.05	0.06

Source: Agarwal and Gort (1996)

In sum, all these studies demonstrate a shakeout in the number of producers. Our data for the commercial jet engine industry highlight a different pattern, as the number of firms increases from 1958 to 1997, without any evidence of exit. While our analysis is at the product level, precisely the jet engines for large commercial aircraft, the previous studies do not specify the definition of the industry. We believe that a finer level of aggregation is required to identify the underlying structural dynamics of the industry. As was stressed by Agarwal (1998), the relevant unit of analysis of ILC models is the product, not the whole bunch of products supplied in an industry. Differentiated dynamics at the product level could be hidden adopting a higher level of aggregation. For example, if the category includes military engines, it is reasonable to suppose that the high growth in the number of firms during the first stage could have been fuelled by the military needs for the Second World War, while the shakeout could have reflected the exit of military engine producers after the end of the War.

According to our data, the commercial jet engine industry is still at the first stage of the Klepper and Graddy (1990) classification or at the second stage of Gort and Klepper (1982) and Agarwal and Gort (1996) studies. In fact, the evolution of the industry is marked by a small number of entry events distributed over 40 years of industry evolution, by no exit events and by a resulting slowly increasing number of firms. As the industry does not experience any exit, the stages of shakeout and stabilisation do not occur. Within the unique stage of industry evolution, changes in technological and market uncertainty give rise to differentiated patterns of industrial evolution. We identify three different periods based on major entry events: 1958-1966, 1967-1980 and 1981-1997. It is important to note that these are not stages in the ILC sense, but periods within the initial stage.

The description of the industry is focused on the evolution of technology and of market requirements, and of the resulting structural dynamics in terms of entry and exit. On one hand, the nature of technical uncertainty and the drivers of technical advances are examined, while on the other hand the impact on engine production of airline demand is analysed. In this section, the analysis of the industry evolution within these three stages is preceded by an examination of the period of early introduction of the jet for military applications. The description of this period is useful for understanding technical and market uncertainty and for identifying the pool of potential entrants into the commercial market.

3.1 The evolution of technology and industry

3.1.1 Early introduction of the technology and potential entry

From the beginning of the powered aircraft industry until the Second World War, the propeller-piston engine combination was the predominant 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 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*, 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 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 3 shows the composition of the industry in the period 1940-1955. The number of piston engine manufacturers decreased from 1940 to 1955. Soon after the war 12 companies were developing and producing jet engines for military applications. Their number increased to 26 in 1955.

Table 3. Number of firms in piston and gas turbine engine industry, 1940-1955

Year	**1940**	**1945**	**1950**	**1955**
Piston	89	58	35	18
*Large**	*22*	*23*	*11*	*12*
Gas Turbine	-	12	24	26

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

Many efforts were made to apply the gas turbine engines to airliners. Engines efficient enough to power airliners were at first 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). Government played an important role in supporting manufacturers of military aircraft and engines.

Research sponsored by the National Advisory Committee on Aeronautics (NACA) and university research was made available to all aircraft manufacturers (Klein, 1977). 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 4 summarises the number of engine manufacturers active in the industry from 1940 to 1955, distinguished by the engine technology adopted. It also indicates whether gas turbine producers did have experience in the commercial market. As shown in the table, 10 firms entered the military jet industry but did not produce civilian engines. 9 out of the 26 companies which developed and produced jet military engines during the period 1940-1955 were also supplying engines for the commercial market. Of the 63 piston manufacturers, 6 were large and potential jet engine producers but none of these actually entered.

It is reasonable to suppose that the set of firms with the commercial capability to produce jet engines comprised at least 9 companies (third row of Table 4)[3]. They could potentially enter the market for jet airliners by joining the technical knowledge accumulated in the development of the turbojet engine with their previous experience of production for the commercial market.

Table 4. Potential entry, period 1940-1955

New entrants in gas turbine			10
Piston manufacturers which entered gas turbine			16
commercial market		**9**	
civil piston and gas turbine	*3*		
civil piston	*5*		
civil gas turbine	*1*		
Piston manufacturers which did not enter gas turbine			63
*large piston manufacturers**		*6*	
Total			89

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

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

However, 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*. The notion of *technological barriers to entry* (Marsili, 1999, 2000) which played a role in limiting *mass entry*, cannot explain why only a very small number of firms actually entered the commercial jet engine industry.

On the technical side, the introduction of the turbojet had a strong impact on aircraft design. The first jet engines powered conventional airframes which had previously been powered by piston engines. After the war airframes were unsuited for the new performances and functionality that the jet 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, and the durability. All these problems had not been revealed by military experience[4]. This stage of technological co-evolution 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. 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].

[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" (*Jane's All the World Aircraft*, 1948).

[5] If the engine is developed for both military and civilian purposes, the two versions go to the tests required for the civil version, because of the presence of more stringent airline requirements.

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. 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 problem was probably more commercial than technical: companies were facing this uncertain perspective as to 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 in the commercial market. The uncertainty of airline companies and the resulting size of launch orders influenced the entry decisions of aircraft and engine manufacturers (Sutton, 1998).

3.1.2 First period: 1958-1966

The first period is defined by the introduction of large jetliners into the market, which 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 1952 the de Havilland Comet, powered by a Rolls Royce jet engine, entered the market but it failed[6]. In 1958 the modified version Comet IV 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.

[6] It experienced more than one accident, because of technical problems of metal fatigue in aircraft. It lost certification and all aircraft were withdrawn from service (Miller and Sawers, 1968; Bright, 1981; Sutton, 1998).

Companies such as General Electric, the first to develop a jet engine in the US, followed a more cautious entry behaviour, avoiding excessively early introduction of gas turbine engines in the commercial market (Miller and Sawers, 1968), probably through misjudging the potential of the civilian segment (Bluestone, Jordan and Sullivan, 1981). General Electric experimented with entry, by powering the unsuccessful Convair 880 and 990, which survived only for a few years. 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 company that the future lay in jet engines" (Fausel, 1990). Allison decided to enter the turboprop market, probably considered less risky than the turbojet.

New jet-powered aircraft provided higher speeds, 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.

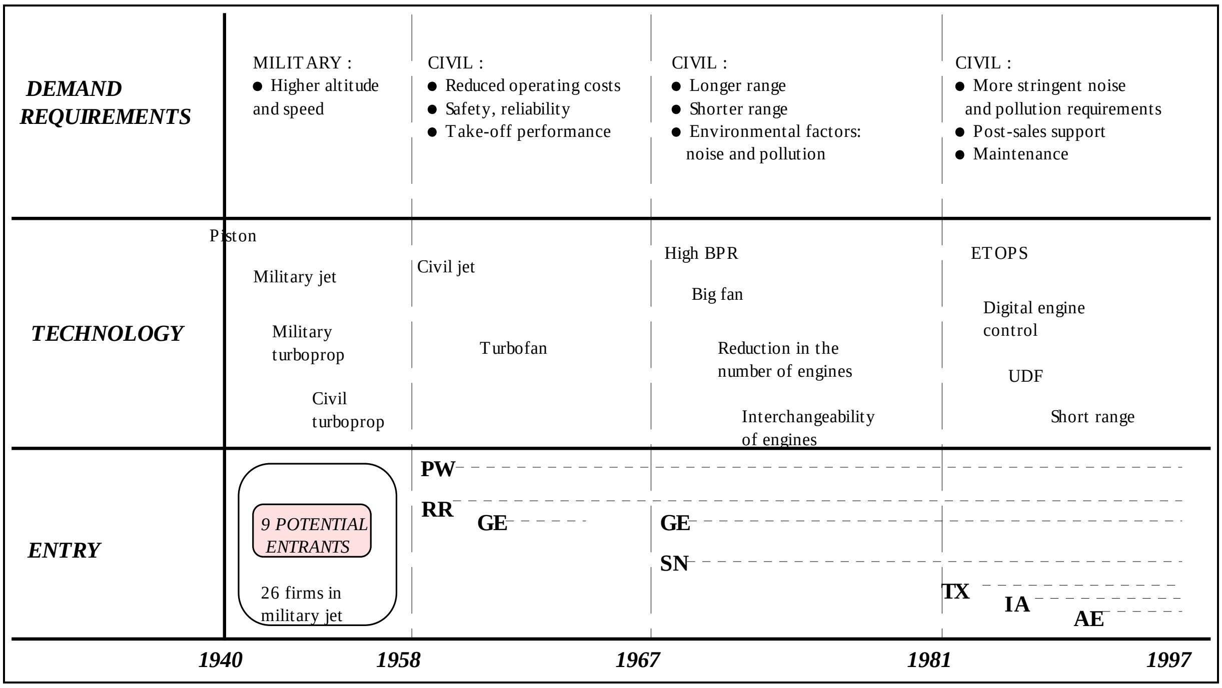
Further design innovations in the turbojet, such as the turbofan, provided much greater propulsive efficiency and supersonic performance[7]. The first turbofan engine was the Conway, introduced by Rolls Royce in 1960. The success of the Conway induced the rival Pratt & Whitney to adopt the turbofan, which emerged as the dominant design.

Technical and market uncertainty as explained above had two important effects:

[7] 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.

- 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, successfully developed turbojet engines for airliners).

Figure 1. The evolution of jet engine technology and industry



1.1.3 *Second period: 1967-1980*

The transition towards the second period 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.

The growth of market orders starting in 1964 connoted 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. Data published by IATA also shows a continuous increase in passenger air-miles over this period, where the average yearly rate of growth was 16 per cent.

On the technological side this period was characterised by technological advances in different fields. The by-pass ratio (BPR) increased enormously with respect to the first jet introduced[8]. The number of engines shifted from 4 to 2, as the twin engine capabilities exceeded the three or four engines they replaced in terms of fuel savings and increased payload (Bethune, 1994). Big fan engines were developed and introduced into the market.

A major change occurred at the design level, permitting 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 aircraft manufacturers. While at the beginning 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. Multiple sourcing policies began to be adopted at the aircraft program level. This played a key role in the emergence of General Electric as a turbojet power. Major engine companies attempted to enlarge their market by supplying different users, especially all the big aircraft manufacturers (Boeing, Douglas and the new entrant Airbus). 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. However, dual or multiple sourcing is only possible when high suppliers' up-front costs can be recovered over large volumes[9].

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[8] General Electric developed a military engine with a BPR of 8:1, which was subsequently used for civil purposes (Norris and Wagner, 1997).

[9] Some scholars analysed the pros and cons of sole, dual and multiple sourcing from the economic and managerial points of view (Bailey and Falmer, 1982; Demski et al., 1987; Riordan and Sappington, 1989; Richardson, 1993; Asanuma, 1985; Sako, 1992).

Companies began to develop families of product designs, based on the concept of "robust design" (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 R&D and 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.

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. Competition between the two started to occur in the segment of aircraft carrying 40-80 passengers (Schaffler, 1991). Second, with the introduction of the big fan engines, wide-body aircraft such as the B747 came into the market.

At this 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.

1.1.4 Third period: 1981-1997

By the 1980s noise and pollution regulations, fluctuating fuel prices and airline deregulation became the main determinants of the technical evolution. High by-pass ratios enabled lower noise levels, and by the 1980s had also become available for short and medium range aircraft (Gallois, 1994). The development of the UDF (Unducted Fan), or ultra by-pass engine, promised roughly the same speed as a conventional turbofan, but with large fuel savings (Hayward, 1986). Developments in engine testing were carried out to extend the engine lifetime, while conforming to the standards of safety and airworthiness (Dawson, 1984). ETOPS (extended twin engined operations) had 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).

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. Airlines have started to outsource maintenance activities and inventory of spare parts to engine manufacturers, which are introducing programmes of logistic and material management (Walker 1996; Doyle, 1997; Seidenmann, 1998). Once major engine manufacturers supply the largest aircraft producers, they become increasingly geared toward marketing to airlines rather than only to airframe manufacturers. They can enjoy economies of scale in marketing activities by offering after-sales, repair and management services to many customers.

At this 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. 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[10].

1.2 Interpretation of the industry evolution

Our data show significant variations with respect to the events predicted by life cycle models. Precisely, the shakeout pattern does not occur: the industry does not experience any exit, but rather a few events of entry during all its life. In terms of the conventional ILC models, the entire history of the commercial jet engine industry corresponds to the first stage. Within this stage, we observe some interesting facts:

- the birth of the industry is characterised by limited entry: while at least nine companies possess 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 and Rolls Royce) bet on the civil application of the technology;
- other events of entry occur during all industry life while there are no exits.

The history makes clear that limited initial entry is not due to traditional notions of barriers to entry or to *technological barriers to entry*, but to commercial and, as we will explain in the next section, to *relational barriers to entry*.

The detailed description of the jet engine industry life cycle leaves us with two puzzling questions. First, what influenced entry decisions? In particular, why potential entrants did not enter at the birth of the industry? Why there were several entries, even at stages in which the emergence of large incumbents could be a deterrent?

Increase in demand may explain, with some delay, the entry of General Electric and SNECMA in 1967, but not the later entry of Textron, International Aeroengines and Allison. Long run expected

[10] 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.

profitability may explain the intermediate entries, but not the latter, particularly after the near bankruptcy of Rolls Royce in the 1970's.

Second: what prevented exit? Barriers to exit are a substantial factor in the industry, but are not a sufficient explanation. Barriers to exit, to name an example, did not prevent the exit of Lockheed and McDonnel Douglas in the commercial aircraft industry, nor the exit of Rolls Royce in the turboprop engine industry.

We believe that existing theories are not sufficient to explain the observed patterns. Many companies were already legitimated through the presence in the old piston engine industry. The high costs of development and the length of the development process make very difficult to consider informational signals as determinants of entry. Finally, technological-based explanations of industry life cycles would induce more entry for a radical innovation like the introduction of the jet engine, which is one of the two most important innovations in the entire history of the aircraft industry.

We claim that both entry and (non) exit have been influenced by the structural evolution of the network of vertical relations. As it will be shown, the structure of the network changed significantly during the life of the industry. These changes had a remarkable impact on entry and exit.

4. Network dynamics and evolution of the industry

In order to create an alternative theoretical explanation for the observed structural evolution of the industry, we study the analysis of the network of vertical relations between engine and aircraft manufacturers. A network is an input-output matrix whose cells contain exchange values between *individual* firms operating in two vertically related industries. The network at each point in time is represented by a biadjacency matrix of a bipartite graph with binary values (i.e. an exchange either exists or does not exist). In this paper we use measures of network for each year of the life cycle of the industry, based on individual data on transactions between aeroengine manufacturers and aircraft producers. The network of vertical relations between each individual supplier and customer in the two industries represents the transmission mechanism of the effects of the evolution of the user industry to structural dynamics of the supplier industry (Bonaccorsi and Giuri, 2000b).

We believe that the *process of creation of vertical linkages* captures the characteristics of technology and of the demand regime[11]. 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, reflects consideration on technological learning which takes place within a single relation and from heterogeneous relations. It has been proposed that a significant portion of technological learning takes place within inter-organisational relations. The notion of learning by using (Rosenberg, 1982) and user-producer interaction (Lundvall, 1988; von Hippel, 1988) have been proposed to describe the form of detailed learning that originates, in very specific technological domains, from the interplay between largely idiosyncratic user requirements and design skills. This is even more relevant in industries in which heterogeneity of technical solutions and final products is very important. Finally, the network structure may influence the rate of technical progress and the technological competition among firms. One can expect that more dense network structures fuel an intense competition among players, that invest to stay close to the technical frontier.

We will show through a re-examination of the history of the commercial jet engine industry how the change in the nature of technical and market uncertainty and the evolution of technology and demand are closely reflected in the dynamics of the network in the three stages of industry evolution. The evolution of network over time is represented by using synthetic measures of the structure of the vertical relation between aircraft and engine manufacturers for each year of the period.

The structure of the network at the beginning and in the year of transition between stages is shown in Figure 2. 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[12].

The network dynamics is represented by measures of relational density and of engine group centralisation for each year of the three periods, which are computed separately for the entire network and for the core. Figure 3 displays the relational density and group centralisation for the entire network and for the core, while Figure 4 presents the decomposition of the index which disentangles the effects on density of entry of new actors (denominator) and of increasing relational activity (numerator). Changes in the network structure are interpreted as indicators of changes in the underlying determinants of the industry life and provide an explanation of entry and exit.

Subsections 4.1, 4.2 and 4.3 present the evolution of network for each of the three stages, while subsection 4.4 offers an explanation of entry and exit in terms of network dynamics.

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

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

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[11] We focus in this analysis on the first layer of demand for engine manufacturers, which is represented by aircraft producers. The second layer is represented by the airlines, which increasingly gained power over time to choose the engine supplier and to determine the technical specifications of the engine to be integrated into the aircraft. Although we recognise that the consideration of the vertical relations with airline companies would provide a more complete specification of the demand side, we limit this work to the analysis of the relation between engine and aircraft manufacturers, as they reflect more carefully the technological content of the relation. Consideration of airlines will be the subject of future research.

[12] Network measures are presented in Appendix 1.

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 competencies over a few basic designs. In general terms, consideration of development costs *mediates* the relationship 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, in intermediate good industries, the test of the properties of products can be performed by producers in relative isolation from users. This is not the case for complex intermediate products which must fit together with 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 trajectories. There was no significant learning from variety (learning from heterogeneous suppliers).

The combination of fundamental uncertainty and relational learning thus explains the structure of the network at stage 1. 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 2, years 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 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.

The network dynamics is evident by looking at the density (Figure 3). The entry of aircraft manufacturers in single sourcing determines a decreasing level of density, which however reach its highest level in 1966, when some cases of dual sourcing occur[13]. In the core of the network the density was close to the maximum value. 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 3).

The dynamics of the network at stage 1 also influenced the development of technology. A dominant design emerged in the configuration of engine-to-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.

[13]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.

Figure 2. Network structure in 1959-1966-1980-1997[14]

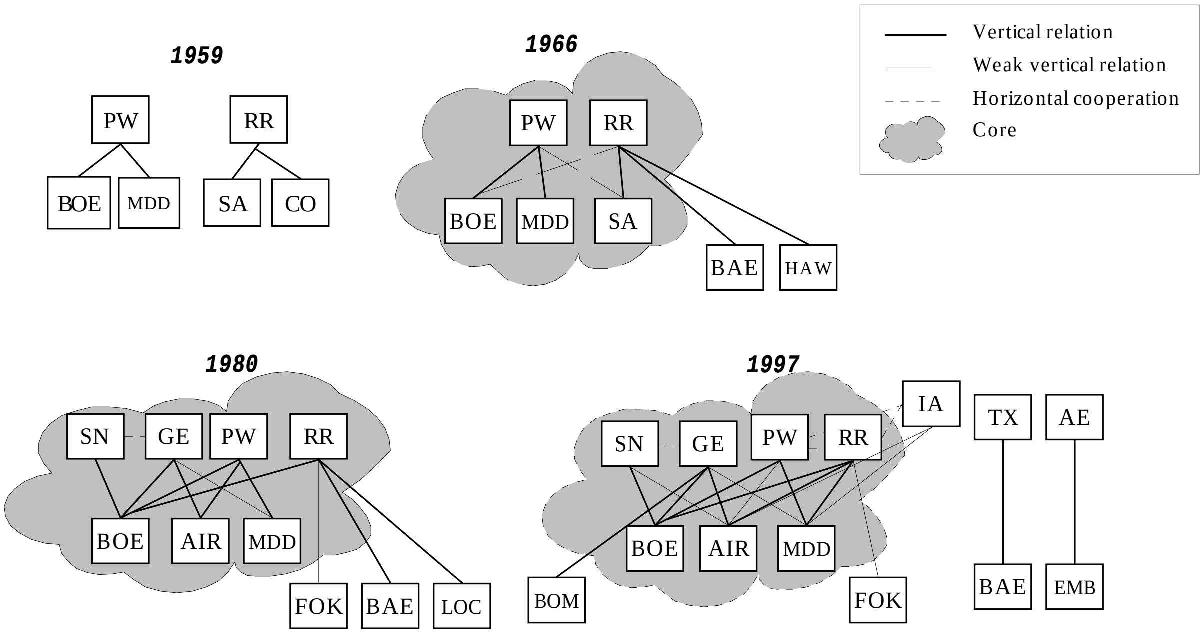
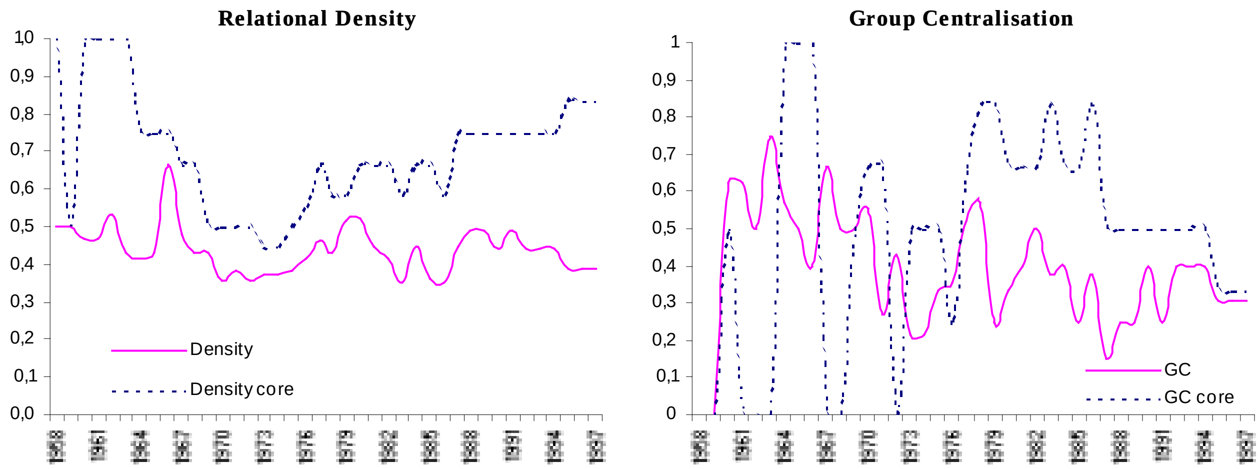
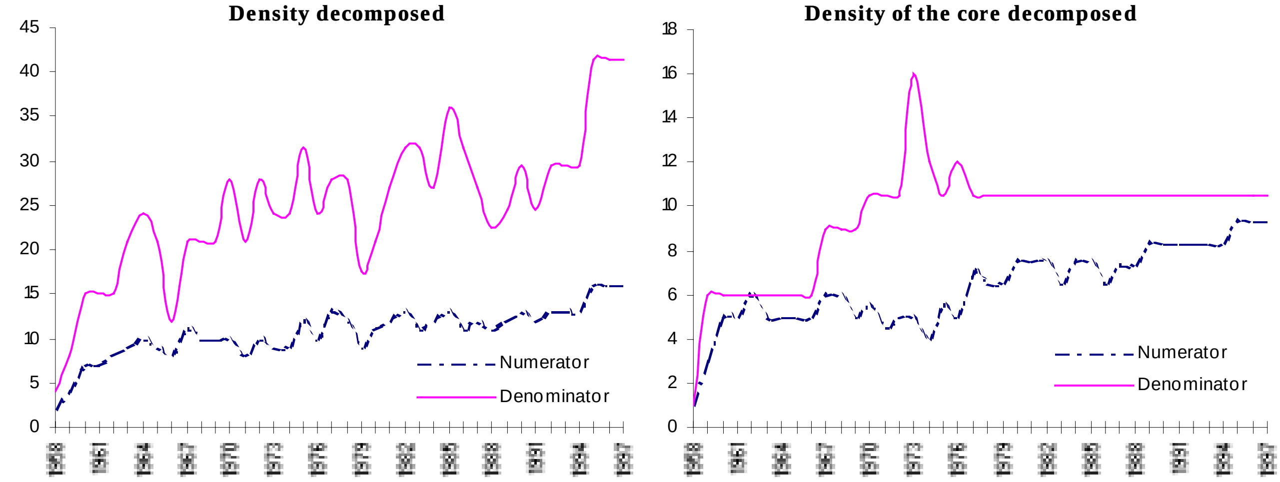


Figure 3. Relational density and Group Centralisation



[14] Company names are reported in Appendix 3.

Figure 4. Relational density decomposed



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

In the second stage two factors lead to the structural change of the network: the resolution of fundamental technical uncertainty and the growth of demand.

The demonstration of viability of the integration of the jet technology with commercial airframes relaxed the constraint of single sourcing. The technical and design interdependence between propulsion, structure and aerodynamics began to be understood more in detail, so that interface parameters could be identified. The risks and costs associated with the potential divergence of technological trajectories of engine suppliers were mitigated. 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: 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).

It was then possible for a single aircraft manufacturer to integrate engines made by two or more different engine suppliers, with a reasonable level of additional costs, mainly due to idiosyncratic investments into design routines and operational procedures. 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 sharp increase in demand which took place in the 1960's also increased the value of having multiple sources of supply and helped to absorb the additional costs.

The network changed its structure completely (Figure 2, year 1980). Other aircraft manufacturers and two large engine suppliers (General Electric and Snecma) entered the industry. The evolution of the network was characterised by diffusion of relations. Each customer looked for supply relations with more than one engine manufacturer and opened new relations. On the supplier side, the introduction of robust designs brought about the possibility to adapt the product to the evolving needs of different users.

The decomposition of density in stage 2 (Figure 4) 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 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 3). Within the core, the dynamics was similar but the number of new relations opened by central actors increased more rapidly. At the end of the stage almost all actors had mutual access to each other and density was as high as 0.7.

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 stage 2 the structure of the network allowed all engine suppliers to get access to central customers. 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 stabilising effect on the network. On the other side, technological innovations could rapidly be made available to all aircraft manufacturers.

4.3 Third period (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 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 meeting the requirements of final customers; second, by the level of post-sales support and maintenance services offered to airlines.

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 relations and sub trajectories. If this is the case, then 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 call access, that is, by the collection of technological sub-trajectories they can pursue. The larger the number of customer relations, the richer the specific learning - an effect we can "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.

A few smaller companies entered the industry in stage 3. 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 3). The high density of the core acted as a barrier to entry for engine manufacturers.

While the density of the network still declined, although slowly, due to entries (Figure 3), the density of the core sharply increased and stabilised at high levels. 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 few relations and those mainly with non-core actors.

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.

Table 7 summarises the relation between technology and demand characteristics and the network structure in each stage.

Table 7. The evolution of technology and demand and the structure of the network

	TECHNOLOGY AND DEMAND	NETWORK
1ST PERIOD: 1958-1966	• fundamental type of uncertainty • high cost of development and testing, high R&D investments • complex intermediate product integrated in a larger system • resolution of uncertainty requires the interaction with the customer - *relational learning* • high investments in specific relations - *aircraft single sourcing*	↳ *PARTITIONED NETWORK* ↳ CLOSE AND STABLE RELATIONS ↳ LIMITED ENTRY AND A FEW TECHNOLOGICAL TRAJECTORIES EXPLORED WITHIN STABLE RELATIONS
2ND PERIOD: 1967-1980	• change in the nature of uncertainty: technical development for specific applications • resolution of uncertainty requires the interaction with a variety of customers - *learning from heterogeneity* • *multiple sourcing* strategies: opportunities to entry	↳ DIFFUSION OF RELATIONS ↳ DENSITY DECREASING (ENTRY) AND THEN INCREASING (NUMBER OF RELATIONS) ↳ INCREASING DENSITY OF THE CORE
3RD PERIOD: 1981-1997	• technological progress to meet specific requirements • marketing to airlines: post-sales and maintentance support	↳ *HIERARCHICAL NETWORK* ↳ NETWORK STABILITY ↳ HIGH DENSITY OF THE CORE ↳ LOW GROUP CENTRALISATION: NO LEADER IN THE NETWORK

4.4 Entry, exit and network dynamics

At the birth of the industry *entry* was limited not only by the limited size of the market, the high costs of R&D or the large technological and market uncertainty. Instead, the *partitioned structure of the network* prevented further entry.

The type of technological uncertainty which dominated the early stages of jet engine called for dedicated, exclusive relationships between airframe and engine developers. There was no room for aircraft manufacturers to work with several sources of supply simultaneously, because the degree of technical and design interdependence was simply too high[15]. Exchange relations took the form of a "monogamous marriage". With this partitioned structure of the network, entry was limited not just by the absolute size of the market, but by the limited number of gateways to enter the market. With airframe manufacturers following a strict single sourcing strategy, each new aircraft programme was

[15] Without considering the differences between consumer good or intermediate good industries, Geroski (1995) observes that for consumers "learning by experimentation can occur through a comparison of the new products which appear in the market, and, almost by definition, entry is the major source of this proliferation of new product varieties". On the contrary, in this industry experimentation occurs through established relations with incumbent suppliers, thus limiting innovative entry.

an opportunity for incumbents, not for new entrants. Therefore, there was no room for further entry once the network crystallised.

In stage 2 *the changing structure of the network* explains the second wave of entry. After the emergence of the turbofan as dominant design and the reduction of technological uncertainty, large aircraft manufacturers switched towards dual and multiple sourcing. The structure of the network changed, from sparse and partitioned to dense. 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. Therefore, new opportunities were open for entrants in the core of the market. In fact, General Electric and Snecma did not enter by supplying small aircraft manufacturers or to fill uncovered niches of the market, but rather addressed the core of the market in direct competition with established leaders (this is not a sensible strategy from the point of view of ILC theory).

Finally, entry still occurs at a later stage of industry evolution. Again, it is not clear from ILC theory why should new entrants enter so late, not only after the emergence of dominant design, but also after another major entry. Over the years, technological evolution continuously lead to decrease the size threshold below which jet technology was not convenient. New aircraft manufacturers entered the regional jet market, in competition with traditional turboprop manufacturers. In 1978 the deregulation of the US market opened huge opportunities for small jets.

The *hierarchical structure of the network* carefully reflected these events. Small aircraft manufacturers entered the network, but because they operated with just one engine manufacturer, they did not get access to the core of the network. This opened opportunities for new entrants, which tied themselves to regional jet manufacturers with almost exclusive relations (as in the case of Allison, supplying Embraer, and Textron, supplying BAe). A periphery expanded in the network. The joint venture International Aeroengines, instead, entered by supplying directly large aircraft manufacturers in the core, because it was dominated by the established actors Pratt & Whitney and Rolls Royce.

The final configuration of the network is then of hierarchical type, with a core and a periphery. Entry is no longer permitted in the core, because there all incumbents have access to all customers, so that entry would be deterred. Entry is instead still permitted in the periphery.

Let us now consider *exit*. The lack of exit is a remarkable feature of this industry. Why the emergence of dominant design did not lead to the superiority of incumbents, so that even a *small number* of new entrants could be deterred or rapidly eliminated?

The approaches based on information contagion provide explanation for exit deriving from static efficiency in production. In organisation ecology competition in an environment with *limited* resources is a determinant of exit.

The theory of ILC offers two complementary views of the reasons behind exit. One is based on the idea that product standardisation brings about static increasing returns, mainly in manufacturing, that make an initial size advantage become cumulative, leading to the exit of smaller and less efficient firms. The other is based on a dynamics notion of distance from the technological frontier. Here the idea is that those firms that cannot keep the pace of investments needed to control the frontier of technology, loose gradually ground, and finally are forced to exit. The common trait underlying these factors 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.

During the first period of industry evolution, the network took a partitioned structure. This means that engine manufacturers had access to differentiated opportunities for learning, with potentially divergent sub-trajectories. This changed drastically in the second stage, with the diffusion of network relations. The increase in density lead to a process of equalisation of opportunities - i.e. all suppliers had access to all customers' specific sub-trajectories. No incumbent could benefit from exclusive access to a customer and its technological sub-trajectory.

Interestingly, while during the first period engine manufacturers explored a limited region of the frontier, following just one sub-trajectory, in the second period they were able to learn in most of the regions. Under these conditions, conditional on the level of investments in R&D, all competitors find themselves close to the technological frontier[16]. This structural change of the network made it difficult for incumbents to gain a decisive lead with respect to competitors. A network with a dense core may prevent exit because there are the conditions for the technological advantage becoming cumulative.

Finally, the third period witnesses further entry, and again, no exit at all. Note that during the same period several customers exited: Lockheed and McDonnell Douglas in the large transport market, and Rombac and Fokker in the regional jet market. The structure of the network helps to explain this pattern: in the third stage the network becomes hierarchical, with a dense core and a sparse periphery. Why there is no exit in the periphery? The reason is that in the periphery the level of competition is lower. Large incumbents in the core do not have strategic interest in following small customers' technological sub-trajectories and leave them to small engine manufacturers. The same factors that induced entry in the third period are also responsible for explaining the survival of entrants.

Let us combine our arguments about entry and exit. The partitioned structure in period I favoured the entry of a small subset of potential entrants. The diffusion of relations in the transition period II favoured the entry of other firms in the core and prevented exit from the core. The hierarchical configuration in period III favoured entry and prevented exit in the periphery, while leaving high turbulence in the core.

It is interesting to note that in the later stage the hierarchical structure of the network "filtered" the dynamics of concentration and shakeout taking place in the downstream industry. While the jet aircraft industry underwent a severe process of shakeout (Sutton, 1998), the jet engine industry, which clearly has no opportunity for diversification, did not. The prediction arising from our discussion is that, if the network had maintained the partitioned structure, the jet engine industry would have undergone a rapid shakeout.

5. Conclusions and implications

We propose that in vertically related industries the notion of network captures certain essential features of the technology and demand regime, and provides a basis for the explanation of the structural evolution of the industry. We have shown how the evolution of technology and market demand is closely reflected in changes in the structure of the network, and how the network dynamics explain the pattern of entry and exit.

The transition from a partitioned to a hierarchical network structure reflects important changes on the buyer side, i.e. the shift from single to multiple sourcing, and on the technological side, i.e. from specific learning within a relation to learning from heterogeneity. The emergence of a core in the network also influences the process of technological competition.

The detailed interpretation of the process of creation of vertical linkages, and the resulting dynamics of networks, allow drawing some implications in terms of entry and exit patterns in ILC models. The process of hierarchisation of the network created room for entry and prevented exit.

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.

[16] This proposition will be formally tested in a work in progress, in which we use Euclidean distance from the frontier as indicators of technological capabilities of firms.

Appendix 1: Network measures

Network indicators are drawn from contributions to social network analysis and adapted for the analysis of vertically related industries (Scott, 1991; Wassermann and Faust, 1994; Borgatti and Everett, 1997)[17].

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". 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 matrix A exhibits 1 in that position. We use dichotomous ties (matrix A), instead of value ties (matrix B), to compute different network indicators.

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.

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

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.

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

Appendix 2

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

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