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Discontinuities, convergence and survival of inefficient trajectories in technical progress

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DISCONTINUITIES, CONVERGENCE AND SURVIVAL OF INEFFICIENT TRAJECTORIES IN TECHNICAL PROGRESS

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1. Introduction

The paper discusses some central issues in the evolutionary analysis of technological progress and of technological competition among actors. It also develops a methodological contribution by building a measure of technology based on multiple technical parameters.

The paper presents an empirical analysis of the technological progress in the commercial aero-engine industry since 1948 to 1997, based on two proprietary databases. The *Atlas Aviation Database* contains all the transactions occurring from 1948 to 1997 between engine manufacturers, aircraft manufacturers and airline companies in the market for large commercial aircraft. For each transaction the aircraft and engine product version is specified. The *AirTech* database contains 16 technical parameters for each 114 engine version.

We develop a multidimensional measure of technical progress through Data Envelopment Analysis (DEA). This mathematical linear programming method builds an envelop of a number of inputs for maximising (minimising) one or multiple outputs. The choice of key technical parameters of aero-engines (SFC, BPR, OPR and Thrust/Weight) and the definition of inputs and outputs has been carried out with the support of aeronautical engineers and purchasing managers of a major airline company. The approach provides for each engine a measure of efficiency based on the contribution of each technical parameter in the overall design of the engine.

The observation over time of the multi-dimensional measure of efficiency shows an increasing pattern evolving through different trajectories. The empirical analysis allow to identify some structural patterns in the technological evolution at the industry the firms and at the firm level.

Some main conclusions are drawn. Technological discontinuities observed at the level of single technical parameters are much more marked than for the multi-dimensional measure obtained through DEA. Technological progress is very discontinuous only with respect to a single parameters while it is more gradual with respect to the bundle of performance indicators linked by complementary relations. Moreover, discontinuities does not only bring about convergence in the space of technical parameters but may open multiple equilibria which allow survival of inefficient products.

The paper develops a discussion of relevant issues in the evolutionary debate on technology and present detailed empirical analysis and cases at the firm level showing common strategies of convergence on the frontier and differentiated strategies of introduction of products below the frontier.

2. Data

The objects of the empirical analysis is the commercial jet aero-engine industries since its birth, from 1958 to 1997. The choice of the aero-engine industry has a number of reasons:

- well-defined brands and generation of products;
- availability of complete directory of data;
- existence of a stable set of technical and performance characteristics representing the product over the history of the industry.

The empirical analysis is based on two databases.

The *Atlas Aviation Database* contains all transactions (orders) occurring from 1948 to 1997 between engine manufacturers, aircraft manufacturers and airline companies in the market for commercial jet and turboprop aircraft. For each transaction the aircraft and engine product version is specified.

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

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

Technical parameters have been classified in technical characteristics and technical performance parameters, or service characteristics with the terminology of Saviotti and Metcalfe (1984).

In a previous paper (Bonaccorsi and Giuri, 2001) we studied the evolution of single technical performance parameters and the technological position of companies with respect to the frontier. The analysis has been carried out at the industry level and at the sub-market level. Sub-markets have been identified through cluster analysis, which classified aero-engines according to 5 selected technical characteristics (weight, length, diameter, thrust, airflow). Cluster 1 represents the smaller segment of the market, including the first turbojets introduced at the birth of the industry, the turbofans introduced at the beginning of the 1960's in substitution of the turbojets, the second generation of turbofans and the small regional jets of the 1990's. Cluster 2 includes larger size-engines while cluster 3 includes the largest engines of the three big players, which power very large aircraft.

The choice of technical parameters and the distinction in characteristics and performance parameters has been validated through interviews with aeronautical engineers and with managers of the purchasing division of a major airline company[1].

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

Table 1. List of product characteristics

Type of characteristics	Characteristics
Technical	Compressor
Technical	Engine type (output)
Technical	Combustor type
Technical	N° fans
Technical	N° LP compressors
Technical	N° HP compressors
Technical	N° of turbines
Technical	N° HP turbines
Technical	Air flow - lb/sec
Technical	Length – inch
Technical	Diameter – inch
Technical	Weight-dry - lb
Technical	Thrust TO – lb
Performance	BPR (By pass ratio)
Performance	OPR (Overall pressure ratio)
Performance	SFC (Specific Fuel Consumption) TO - lb/hr/lb

3. Building multi-dimensional measures of technology

3.1 Data Envelopment Analysis

To develop a multi-dimensional measure of technology we refer to previous contributions on production and cost frontiers (Farrell, 1957), which study the efficiency in combining a set of inputs to obtain a set of outputs.

Before Farrell's contributions in 1957, the empirical literature on the estimate of production and cost frontiers used least squares regression models to explain the relation between a set of inputs and an average level of output. The emphasis was on the *average* production technology rather than the *best* technology. Moreover, no explanation was provided for the significance and the sign of the residuals of the regression. In Farrell (1957) the definition of the production frontier is based on the best technology, and the study of the efficiency is based on the concept of distance from the frontier.

This issue has been developed within an econometric and a mathematic approach. The first is a stochastic and parametric approach and the second is deterministic and non parametric. They differ mainly in two points: the determination of the shape and position of the frontier, and the interpretation of the distance from the frontier, that is the measure of efficiency.

In this work we use the mathematical programming approach called *Data Envelopment Analysis* (DEA), which has been originally proposed by Farrell (1957) and subsequently developed by other authors (Charnes e Cooper, 1985; Knox Lovell and Schmidt, 1988; Norman and Stoker, 1993; Grosskopf, 1993). Its basic characteristics are that it does not require the specification of a functional form with the introduction of parameters, and the combination of inputs and outputs is deterministic, because of the absence of an error term.

The method builds a production frontier by solving a number of mathematical programming problems, and computes a measure of technical and allocative efficiency for each production unit. Technical efficiency is the maximum output given a set of fixed observable inputs (*output oriented*), or the minimum level of inputs given an observable level of output (*input oriented*).

The DEA is deployed in three main steps:

- construction of the set of inputs and outputs;
- computation of the Farrell technical efficiency measure;
- computation of the minimum cost for each production unit and of allocative efficiency.

For the purposes of building a pure technological frontier, we refer to measures of technical efficiency, and not of allocative efficiency, which involve the use of price for their computation.

The technical efficiency (input oriented) is defined as

$Fi(y,x \mid C,S)=\min\{\lambda:\lambda x\in L(y \mid C,S)\}$,

subject to:

1. $\sum_{k=1}^{K} z_k y_{km} \geq y_m$
2. $\sum_{k=1}^{K} z_k x_{kn} \leq x_n$
3. $z_k \geq 0$

in the case of constant return to scale (C)[2] and strong disposability of inputs (S)[3], where:

x_n is the set of $n=1,2,\dots,N$ inputs,

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[2] The model can be built on three different assumptions on returns to scale:
constant returns to scale: $z_k \geq 0 \quad \forall k$;
non increasing returns to scale : $\sum_{k=1}^{K} z_k \leq 1$;
variable return to scale: $\sum_{k=1}^{K} z_k = 1$.

[3] The set of inputs and outputs may have the following properties:
strong disposability of inputs: if inputs are constant or decreasing, output is non decreasing;
weak disposability of inputs: if inputs increase proportionally, output is non decreasing;
strong disposability of outputs: it is possible to freely dispose of outputs (typical assumption about disposability of outputs);
weak disposability of outputs: proportional reductions of all outputs are feasible. However, it does not necessarily follow that reductions in individual outputs are feasible (i.e. the reduction of undesirable outputs may be costly).

y_m is the set of $m=1,2, \ldots, M$ outputs,

z_k is the set of intensities of n inputs and m outputs for $k=1,2,\ldots,K$ units of productions,

Fi is the measure of input oriented technical efficiency,

L is the *Input Requirement Set*, which defines the assumptions on returns to scale and substitutability of inputs.

A firm is technically efficient if Fi=1, is technically inefficient if 0<Fi<1.

The advantages of DEA are the possibility of using at the same time a large number of inputs and outputs, and of obtaining measures of efficiency for both the set of inputs and outputs. Moreover, this approach is not influenced by problems of mispecification of error and functional form.

The main limitation is that every deviation from the frontier is considered as inefficiency, and it is not possible to statistically estimate the deviation from the frontier. As a consequence, it is very important to reduce as much as possible errors of data measurement and of variable selection.

Recent studies are trying to overcome these limitations, through the development of non parametric stochastic frontiers and stochastic mathematical programming approaches.

3.2 Technological frontier in the aero-engine industry

By applying DEA, we develop a technological frontier, which is composed by multiple technical parameters.

The first step is the definition of variables that represent the inputs and outputs in the DEA.

The selection of the technical parameters to be used for the definition of a multi-parameter technological indicator has been done with the support of aeronautical engineers and trough the consultation of technical literature on the structure and functioning of aero-engines (Janes Aero-engines, 1997; libri…)

A good measure of efficiency (distance from the frontier) can be well obtained by combining the following 4 main technical performance parameters, which embody a number of other technical parameters and interactions among them:

- Specific fuel consumption (SFC),
- By-pass ratio (BPR),
- Overall pressure ratio (OPR)
- Trust/Weight (T/W).

The first three are performance parameters, as indicated in Table 1; T/W is a performance indicator built by the ratio of the two technical parameters thrust and weight. Advancements in these parameters depend on innovation in other technical parameters and design characteristics.

The efficiency with which the turbojet converts fuel energy into useful propulsive power is usually expressed in terms of specific fuel consumption. This is defined as the mass flow rate of fuel burned per unit of net thrust produced (Janes Aero-engines, 1997).

For the application of DEA we defined SFC as the output of the process, and BPR, OPR and T/W as inputs, which are all related to the output SFC.

BPR is “the ratio of the air flow bypassing the core of the engine to the air flow entering the core” (Janes Aero-engines, 1997).

OPR is “the ratio of the outlet pressure from the compression process to the inlet pressure to the compression process” (Janes Aero-engines, 1997).

Thrust is a design parameter, which is directly related to the weight of the engine. The intensity of the relation is a performance parameter. In fact for having an increase in thrust, the weight of the engine also increases, and this reduces efficiency. The ratio T/W can keep constant only if there is technological innovation.

The inputs and outputs are related in the following way.

SFC is influenced by the propulsive efficiency expressed by BPR. The propulsive efficiency is the ratio of the useful propulsive power applied to the aircraft to the kinetic energy of the gas leaving the nozzle. There is an inverse causal relation between BPR and SFC. At the same time a high BPR increases weight and can negatively affects OPR.

SFC is also inversely influenced by the thermal efficiency, which is “the ratio of the kinetic energy of the gas leaving the nozzle to the fuel energy” which depends on the OPR.

There is also a functional relation between T/W and SFC. However the relation between the two parameters is not direct, but it is mediated by other technical. For having technological advance, the direction of the relation has to be negative.

The second step is the computation of the level of efficiency of each aero-engine, which is carried out by using the software OnFront 2 (Fare and Grosskopf, 2000), designed for efficiency and productivity measurement.

For the purposes of this study, the suitable approach is the output oriented. However, in OnFront the output oriented approach maximises output given a set of a fixed observable inputs. Our objective is the minimisation of output (specific fuel consumption) given a level of inputs. To solve a computational problem due to the lack of the procedure in the software[4], we use the input oriented approach (minimising inputs given a level of outputs) considering the output SFC as input to be minimised and the inputs OPR, BPR and T/W as given outputs.

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[4] The software allows minimisation of outputs for determining allocative efficiency in a cost frontier. However, the optimisation problem of the cost frontier, which requires the use of price data, is different from the objective of determination of a pure technological frontier.

We computed the efficiency under the assumptions of constant returns to scale and strong disposability of inputs and outputs. We also computed the efficiency under the other assumptions defined above. The results were highly correlated, and we presented the results with the standard assumptions.

The result of the application of DEA is an index of efficiency for each aero-engine in a scale 0-1. An index close to 1 indicates a high level of efficiency in the combination of inputs and outputs, an index close to 0 indicates a low level of efficiency. Notes that 1 represents the best combination of inputs and outputs among the 114 aero-engines analysed. The efficiency index for each engine is presented in Table 2.

Next section will discuss the results of the empirical analysis.

3.3 *Technological progress*

The rate of technical progress is determined by calculating 3-year rates of change of the level of efficiency over time. The rate of change of the level of efficiency is compared with the rate of change of the single performance parameters to show the presence of major discontinuities in technical progress.

The values of single parameters are normalised on a 0-1 scale to allow comparability with the efficiency measure.

The rate of change is computed as follows

$$T_k^t = \frac{K_{\max k}^{t} - K_{\max k}^{t-1}}{K_{\max k}^{t-1}}$$

where

t = last year of 3-year periods

k = 1, 2, …z performance indicators

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

4. Empirical analysis and discussion

The rich array of data makes it possible to offer an interpretation of the long-term evolution of the jet engine technology both at the level of the entire industry and of individual manufacturers. We focus here on some of the crucial points in the debate on the evolutionary theory of technology, for which we can offer a fresh contribution.

4.1 Gradualism vs. punctuation in the evolutionary process

Figure 1 shows the maximum level of the DEA indicator of each company for each year of the time series across all the industry. Figures 2-4 replicate the representation for the three industry clusters defined above.

The technological evolution is one of sustained progress over a very long period, with remarkable improvements in overall efficiency. The level of the DEA index changes from around 0.2 in the 1950s to a value of 1 in the 1990s.

In the initial period of the history of the industry, the average level of efficiency is around 0.2, a very low level in comparison with the subsequent technological evolution. The cloud of points in Figure 1 include the Avon models based on the initial turbojet technology and the Conway models, with a by-pass ratio of 0.33, and the JT3C and JT4A turbojet engines of Pratt & Whitney. Then there is a first jump to levels of DEA around 0.4 - 0.5 in the following ten years: these engine models incorporate the new turbofan technology and are developed by Rolls Royce (the Spey family) and Pratt & Whitney (the JT3D family). These two families do not undergo any significant change over time in terms of their overall efficiency.

The true radical change in the jet engine technology comes in with the new concept of high by-pass ratio. Models introduced in the early 1960s realise a jump of the DEA index from 0.5 to 0.7, and, more importantly, open a new trajectory that allows a series of further improvements.

Finally, a further jump is visible in the 1990s with the introduction of the very large engines for the B777 (GE90-92, P&W 4074, 4077 and 4090, the RR Trent family).

The overall pattern is one of three discontinuities in overall efficiency, followed by long periods of incremental advancements.

The graphical representation disaggregated at the cluster level (Figures 2-4) confirms the presence of three big jumps in cluster 1. However, in cluster 1 the third important change occurs later than in other clusters, except for CFM International, which enters introducing innovative products with an efficiency level higher than 0.7. Cluster 2 includes all larger families of engines of the third generation with a DEA ranging from 0.6 to 0.9. Cluster 3 shows the jump to DEA indexes of 1, realised by the engines for the larger aircraft (B747, B777).

Does this result support the notion of punctuated equilibrium in evolutionary processes?

Figure 5 shows the evolution of rates of change of single technical parameters and DEA efficiency in the history of the technology in terms of rates of change on a 3--year basis. A clear discontinuity pattern in single parameters emerges, with extremely high rates of change. When looking at the dynamics of the DEA measure, however, rates of change are much lower. There is no sharp discontinuity in the data, but rather an overall upward trend, with some points of acceleration. The overall picture is one of *strong discontinuity in single parameters* and *less discontinuity in aggregate measures of technical performance*.

This finding has two important implications for evolutionary theory.

From a methodological point of view, it must be remarked that most of the discussions on the nature of technological progress, namely, the continuous vs. discontinuous or punctuated nature, is based on the observation of time series of *single* technological indicators, usually referring to a particular technological performance of a product (Sahal, 1985a; Tushman and Anderson, 1986, 1990; Levinthal, 1998). In most cases, this is due to practical limitations in the availability of data for long time series. In some sense, nobody denies that the very concept of technological performance of a product is a truly multidimensional one, but it becomes very difficult to trace many variables over a sufficiently long period to allow significant analysis. So there is a sharp separation between methodologies that use a large array of variables, but with a limited time horizon, such as hedonic price in microeconomics or conjoint analysis in marketing science, and methodologies that trace technological evolution over time, but focussing on a single variable, or methods based on multi-dimensional functions which do not measure technical position of actors (Lancaster, 1971; Saviotti and Metcalfe, 1984; Sahal, 1985; Dodson, 1985; Martino, 1985; Tushman and Anderson, 1986, 1990; Trajtenberg, 1990). This separation is unfortunate, for various reasons.

On a general level, the implicit assumption seems to be that, while in the short run various technological parameters may influence the survival of a product in the market, with many subtle trade-offs, in the long run there is a dominant technological dimension that drives the evolutionary dynamics. Thus computers may differ for a number of characteristics, but in the long run computing power and cost per computing operation are the only things that matter and dictate the intensity of selective pressures. Aircraft may be largely different but in the long run direct operating costs (DOCs) and the number of available seat miles (ASMs) drive the selective success, and so on. In other words, the trade-offs between parameters can be interpreted as random noise around a trend strictly determined by one or a few fundamental dimensions.

This claim seems reasonable, but its empirical validity is still to be demonstrated. Our data show that the dynamics of single technological parameters may deeply differ from the dynamics of an aggregate measure of performance. More importantly, our data show that rates of change of DEA measures are both larger and smaller than rates of change in individual parameters. This means that any conclusion on the nature of technological evolution based on a single indicator is affected by a severe selection bias.

From a substantial point of view, the reason behind the difference between dynamics in single measures and dynamics in aggregate multidimensional measures must be explored. In our case, technology has a strong systemic nature. Technological interdependencies and design complementarities are immensely important. Breakthrough innovations may occur in single components of a product, producing a big improvement in single technical measures, and in the overall system. However, in many systemic products, there is a trade-off in the behaviour of single parts of the system. In this case, a technological discontinuity occurs only when there is innovation at the overall system level. Complemetarities and trade-offs among parts of the system do not allow to consider separately innovation. In fact, once a technical advancement occurs in a system, other complementary technologies must improve for getting a major breakthrough innovation affecting the overall performance of a product.

4.2 Convergence to the frontier

The comparison between the maximum value of DEA indicators at the level of industry and at the level of individual competitors is particularly informative (Figure 6). Looking at the relative position of each manufacturer with respect to the frontier of peak performance, a clear pattern of convergence emerges.

Although technical progress has been sustained over more than four decades and marked by significant jumps, *all competitors converge towards the technological frontier* with their top performing products. The identity of the technological leader may change over time, but the delay with which followers join the leader on the frontier is very small. No competitor stays persistently below the frontier with all its products.

In the first period of the history, Pratt & Whitney and Rolls Royce compete head-to-head and become technological leaders almost at alternate years. There is no technological dominance of a competitor over the other. The innovating entry of General Electric in 1970 was soon followed by the other competitors, which approached the frontier and joined the leader. In the last decade, there is substitution of technological leadership over time, and all major players converge on the frontier in the period 1995-1997.

4.3 Survival of unfit products

At the same time, a significant portion of products launched by all competitors lies below the frontier. Inspection of Figure 7a,b gives an impressive view of the dispersion of individual products in the technical efficiency space.

At any time, we see the coexistence of two seemingly contradictory processes. On one hand, all competitors thrive to lead the technical evolution or to join the leader within a short time frame; on the other hand, competitors go on launching *deliberately* products that lie below the maximum performance they can reach in the same period.

Figures 8-10 offer a complete view of this phenomenon at the company level. We see two paradigmatic cases.

Survival by multiplicity of fitness criteria

This case includes two examples. First, after launching the Spey family in the mid-1960s, Rolls Royce develops several small engines: the M45H and the Tay family (Tay 620, 650 and 651) (see Figure 8). All these models lie well below the frontier of their respective periods, and also below the efficiency levels that Rolls Royce itself was able to achieve with the almost contemporary RB211 family. In this case Rolls Royce was induced to develop these models by the need to get through the US market and by the deliberate choice to serve small customers. In fact, the Tay 651 was introduced in 1980 to enter into the lucrative multi-source B727 market, while M45H equipped the unsuccessful VFW aircraft, and Tay 620 and 650 were developed for the Fokker 70 and 100, respectively.

None of these efforts were commercially successful. After the early technological achievements of the Avon and the Conway, Rolls Royce experienced an immensely difficult period. The Spey family did not break through the large US market, but was mainly sold to European aircraft manufacturers (Hawker Siddeley, BAC, Fokker), largely reducing the financial resources available for further developments. Shortly after Rolls Royce decided to commit itself to a very large engine, anticipating the growth of the wide-body market. Unfortunately, it targeted the most unsuccessful aircraft in the cut-throat competition between the Boeing 747, the McDonnell Douglas DC-10 and the Lockeed L-1011 Tristar. As it is well known, the parallel development of the L-1011 and the RB211 placed the existence of both companies at risk (Newhouse, 1981). Notwithstanding these difficulties, Rolls Royce decided to respond to the needs of the small engine segment with the Tay family, even though they were not based on significant advancements.

A slightly different pattern emerges with respect to the CFM56-7 version of the large CFM family, introduced by the General Electric-Snecma joint venture. As it is clear from (Figure 9), the 7B is the last but also the least efficient version of a large product family, that also happened to be commercially highly successful. This version was developed in order to serve the needs of the new generations of the successful B737 (series 600, 700 and 800). Technically speaking, the 7B version is less performing in terms of overall pressure ratio and fuel consumption.

These two patterns have an element in common. Although in both cases the groups of products lie largely below the frontier, they survive thanks to the existence of technological niches. In these niches users have idiosyncratic functional requirements and value the excellence in a particular technological dimension more than the overall performance.

Note that niches do not imply separate technological clusters or market segments. The examples of sub-optimal groups of products discussed above are integral part of their respective cluster and compete with other products in the same segment. While they are less efficient globally, they are superior to competing products with respect to at least one dimension, which turned out to be decisive for at least one group of users.

There is a difference between the two cases: in the Rolls Royce case, the overall performance of the Tay family stays at the same level of the Spey family; in the CFM, on the contrary, the 7B version is worse. In other words, in one case we have a family extension at the same level of efficiency, by changing the combination of parameters, in the other a downgrading of the overall performance.

We might think of these niches as formed by users that do not have additive fitness functions, that is, they have multiple fitness functions. If the benefits associated to the different dimensions of technological performance of products cannot be expressed through a single measure, then it is necessary to assume that multiple functions are at place simultaneously. Suppose for example that a user group has lexicographic selection criteria: inefficient products may survive if they are superior in at least one dimension, if that matches the most important selection criteria in that group.

Note also that the DEA measure is probably the best approximation to the overall concept of fitness, because it incorporates all relevant inputs and performance outputs, without imposing any functional specification to their relationship. In some sense, DEA is the most abstract representation of fitness in the technological field. The acid test for the modelling strategy based on a single fitness function is to pass a test against empirical evidence that do not pose severe requirements in terms of theoretical assumptions on the aggregation of several dimensions of fitness.

Still, as we shall see, in our case a DEA-based measure clearly shows that a single fitness function does not capture all the technological evolution.

Survival by multiplicity of selection levels

There is a third pattern that merits a careful analysis. Inspection of the Pratt & Whitney and General Electric/Snecma pictures show a number of clouds of products immediately below the frontier. In the case of Pratt & Whitney (Figure 10), the JT3D fan family, the JT8D, JT9D and PW4000 all exhibit a small number of models at the frontier and several models within a close distance. In the JT8D case, for example, early models were at the frontier, while subsequent developments in the following twenty years were all located roughly at the same level of overall technical efficiency. But, contrary to the Rolls Royce case, basically all models were targeted to variants of highly successful aircraft models and were developed at low marginal costs, exploiting robust technological platforms. Thus, while Rolls Royce tried to develop an entire new family with an obsolete technology (and failed), Pratt & Whitney exploited the old family through a large number of low cost, stretched versions, that were sold in large quantities. The strong technological advantage and the large commercial success gained with the top performers of the family (such as the JT8D-7B and 8B with DC-8 and DC-9, and the JT8D-17R) offered an umbrella for other less efficient models, either in absolute terms or with respect to the top available technology in the period.

The same logic applies, although with less dispersion in the space of technical efficiency, to the JT9D family developed for the large B767, B747, DC-10 and A300, and for the PW4000 family. In the CFM case (see Figure 9), the CFM56 family underwent several developments (series 2, 3 and 5), each targeted to different aircraft models, and again a large cloud of below-the-frontier engines is visible during the 1990s.

In this case, survival was due to the extension of the product family. More deeply, selection does not apply to individual products, but to families of products. If strong product families may survive, they can shield from selective pressure and offer protection to weaker individual products.

Implications for evolutionary theory

Summing up, we see several examples in which companies deliberately introduce products that perform worse than they could achieve. In evolutionary terms, we observe unfit entities. These entities survive thanks to two basic mechanisms: multiplicity of fitness criteria or niche creation, and family extension.

These two mechanisms refer to fundamental problems in the evolutionary theory of technology.

The possibility of survival of inefficient products in relatively segregated niches raises the problem of *multiplicity of selection criteria* or fitness functions. Stated differently, it raises the problem of non-linearity in the selection environment.

The possibility of survival of inefficient members of an overall efficient product family raises the problem of the *levels of selection*. While genic interpretations of evolution (à la Dawkins) admit only one level of selection, more recent developments make clear that there may legitimately be several levels: for example, genes, organisms, and communities. As Jablonska (2001) states, it is also possible that the sign of selective pressures is not the same across levels, so that a give trait is evolutionary favourable at one level but negative at another.

Our reconstruction of the evolution of jet engine technology is not compatible with a narrow evolutionary view, which we might label vetero-Darwininian (or à la Dawkins). In this version artefacts mutate randomly at the level of individual technological parameters and are selected on the basis of a fitness function that maps the ensemble of parameters on a real number. There are two important additional assumptions: there is *one* fitness function, and the fitness function is completely *exogenous* to the evolutionary process. If this is true, then abstract properties of the evolutionary process of technologies may be derived from simulation models (e.g. genetic algorithm, NK model) that use a single fitness function and define it exogenously.

As we have discussed elsewhere there is no compelling reason to accept such a vision, other than the need to closely follow a strict *analogy* with the fundamentalist version of evolutionary theory.

In reality, as the contributions in Ziman (2001) clearly show, there are many features in biological evolution which really encourage a completely different modelling strategy. Among other things, it is possible to think of an evolutionary process that is based on *multiple* and *endogenous* fitness functions (Jablonski, 2001; Mokyr, 2001). Allowing for multiple fitness functions implies the existence of several, irreducible selection criteria, with no need to reconcile them through a common metrics. Allowing for the endogeneity of the fitness function means that the outcome of the selection process may have a feedback on selection criteria, so that these change over time.

As a matter of fact, our story calls for a more “liberal” evolutionary interpretation, in which directed mutation is allowed, there are several levels of selection, and selection follows a number of non reducible criteria.

4.4 Structural evolution and discretionary strategic behaviour

One of the crucial points in the debate on evolutionary modelling of technology is whether a structural description captures all the stylised facts or there is some need to incorporate strategic subjectivity. Stated differently, there is debate over the limits to strategic manoeuvring of companies set by structural characteristics of the dynamics of technology, such as paradigms, trajectories, path dependency, inertia and the like (Dosi, Nelson and Winter, 2000).

At one extreme, pure structural models resolve strategic discretionary behaviour as a collection of meta-routines, which govern more or less complex articulations of routines at various levels. The choice of strategy is severely limited by the available repertoire, which in turn is a function of existing competencies. Although various “learning to learn”, meta-levels and abstract or general competencies are introduced, the basic idea is that the intrinsic features of technological learning place severe limitations to the degrees of freedom of companies.

Our detailed reconstruction offers some valuable insights on this debate.

More precisely, we offer an articulation of the relationship between structural technological dynamics and the range of company technological strategies that are compatible with that dynamics.

There are several *structural features* of evolutionary dynamics of technology in the jet engine industry, namely:

- the overall evolution is characterised by three technological jumps, followed by incremental developments;
- there is convergence on the technological frontier by all competitors, at least with their respective top performer products;
- at the same time, there is persistence of sub-optimal products over time, due to the creation of niches and the extension of product families;
- all competitors develop large families of products after having reached peak levels of technological performance;
- entry takes place only in structural holes (see CF6 for General Electric, the CFM family, and the entry of Allison).

There are also variations in the way different competitors place themselves within this structural dynamics and, in turn, contribute to shape it, namely:

- Pratt & Whitney and Rolls Royce follow a strategy of *sequential entry* into different market segments, while General Electric plays a game of late entry into all segments *simultaneously*;
- in the head-to-head competition between P&W and R-R, the former is more rapid in introducing radically new engines and more aggressive in the gradient of change within its product portfolio, while the latter is laggard and more gradual;
- General Electric enters, both in isolation and in alliance with Snecma, with highly superior products from the technological point of view, displacing competitors with aggressive offers;
- the dynamics of introduction of new products is one of point-to-point, cut-throat competition;
- there is an increase over time of the extent of progress allowed by successive platforms: from 0.2 to 0.3 for Spey and Tay in the Rolls Royce case and for JT4 and JT8 for Pratt & Whitney; from 0.6 to 0.8 for RB211 and from 0.7 to 0.9 for CFM56;
- there is also an increase in the length of life of product families, from a few years for Avon, Spey and Tay to many years for the JT3, JT8 and JT9 and for the CFM56;
- the last two trends seem to imply than competitors try to endogenise technological discontinuities, optimising the exploration-exploitation trade-off and making successive technological jumps less disruptive.

Summing up, the overall technological dynamics place severe constraints to the set of feasible strategies. The steady but discontinuous evolution of technologies require a steady flow of investment and the ability to balance inter-temporally the huge financial needs and the cash flows. In order to survive, companies must be able to stay at the technological frontier, at least with part of their product portfolio. All companies must solve in some way an extremely severe exploitation-exploration trade-off.

At the same time, there are some degrees of freedom for variety in strategic approaches. Both leaders and followers can gain market shares. Companies may optimise their product portfolio in different ways in terms of timing and extent of investment. Companies may also play different strategies in terms of the length of product families. Strategic options are constrained but not eliminated by structural features of technological evolution.

No purely structural representation is able to capture the subtle variety of strategic approaches. In turn, the implementation of these alternative approaches may shape the overall dynamics differently. Interestingly, the internalisation of discontinuities that manufacturers pursue through the lengthening of life of families and the robustness of technological platforms have a structural effect, insofar as successive jumps are less radical. The three discontinuities, in fact, involve progressively lower short term rates of change.

Thus we have a feedback effect, from company strategies to the structural evolution. This represents another important contribution to the debate on evolutionary modelling.

4.5 Technological performance and market success

An evolutionary account of technology must acknowledge, ultimately, that selection takes place not on the basis of technological performance alone, but also on the basis of economic considerations. The history of technology and of economic growth is rich of examples where fully developed technologies did not diffuse in the economy until their economics, perhaps due to exogenous factors such as relative prices or raw materials, became attractive (Rosenberg and Birdzell, 1990; Mokyr, 1993; Landes, 1999). Nelson (2001) has convincingly argued that the articulation between selection by the community of technologists based on technical performance, and selection by the community of users based on economic factors is one of the crucial points for a theory of evolution of technology. Although this theme is considered critical, a few reconstruction and detailed stories are available.

We may explore the detailed relationship between technological performance and market success across all the history of the industry.

To carry out this analysis, we preliminarily plotted for each engine the value of DEA index against one indicator of market success: the yearly average number of products sold during its life. In order to make DEA measures and market shares comparable across time, we did not consider in this preliminary exploration all engines introduce since 1990. The plot of data is available in Figure 11.

It is clear from data that there is not a close relation between technological superiority and market success. Not only technological performance and economic value are not synonymous, they are also uncorrelated. If we observe separatedly the three jumps of innovation according to levels of DEA, we cannot detect a positive correlation between the two variables. On the contrary we observe high selling products which in many cases have a level of efficiency lower than the other engines in the same group. This result deserves further analysis and statistical testing to be made more robust and general.

If confirmed, this result has a profound implication on evolutionary modelling. First, we have already showed that, even within the narrow region of technology, a single fitness function and a single selection level do not represent the evolutionary process correctly. To this we now add a new dimension: a comprehensive representation must admit that a new, non reducible, level of selection must be introduced and that a new type of selection criteria are at work in the evolution of technologies.

Technologies evolve following a variety of internal criteria, that are not reducible to any single dimension, and following an endogenous economic dynamics mediated by the market.

The exact relationships between technological performance and market success must be the object of a future detailed study.

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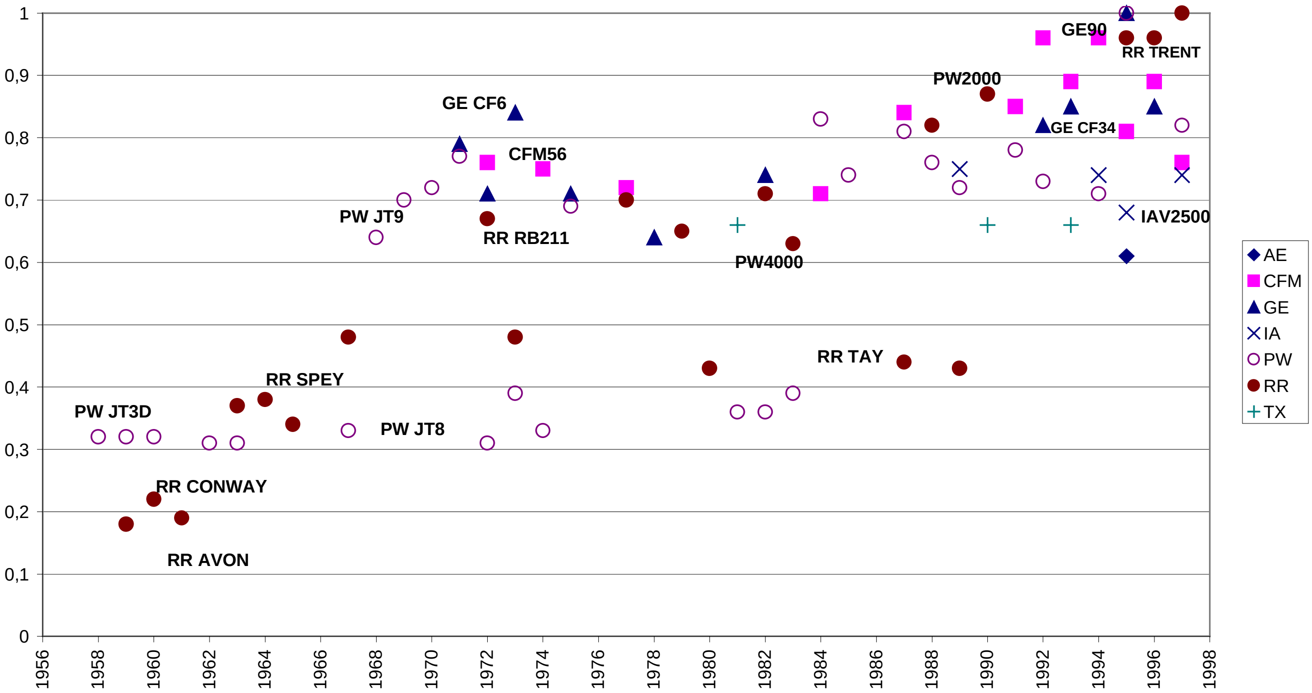

Figure 1 Max DEA efficiency at the firm level

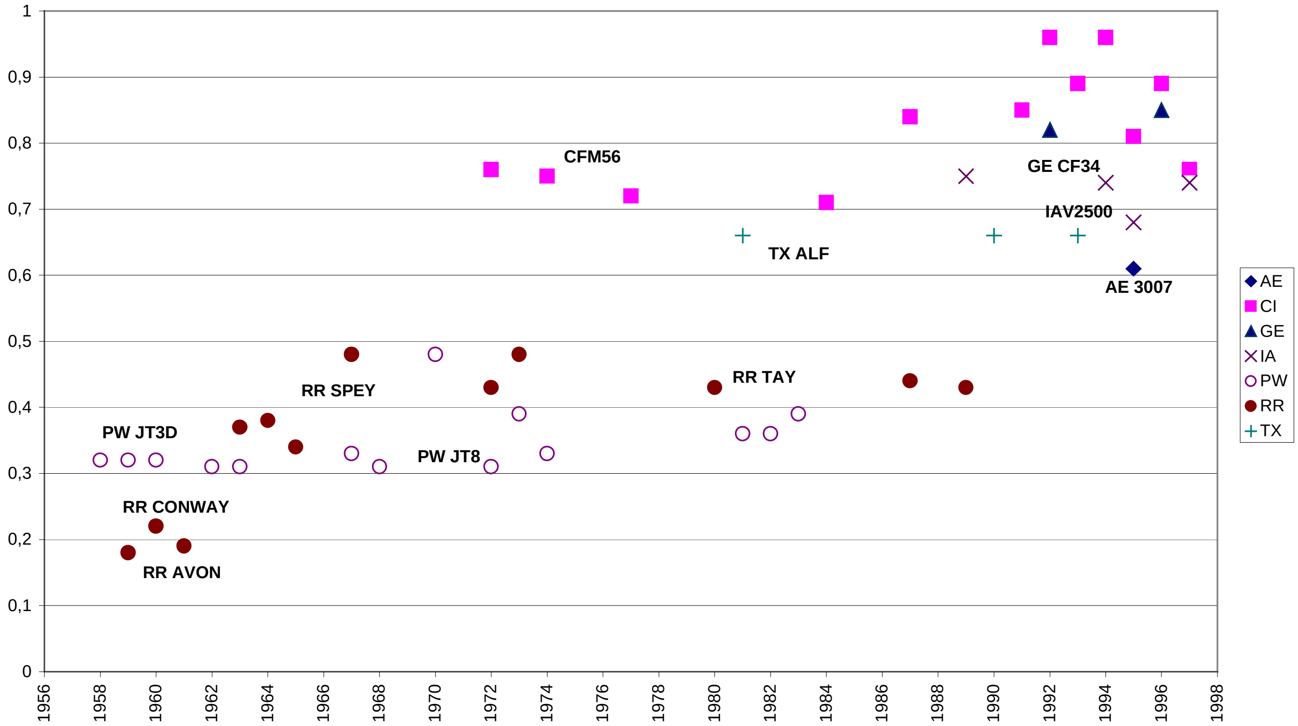

Figure 2 Max DEA efficiency at the firm level, cluster 1

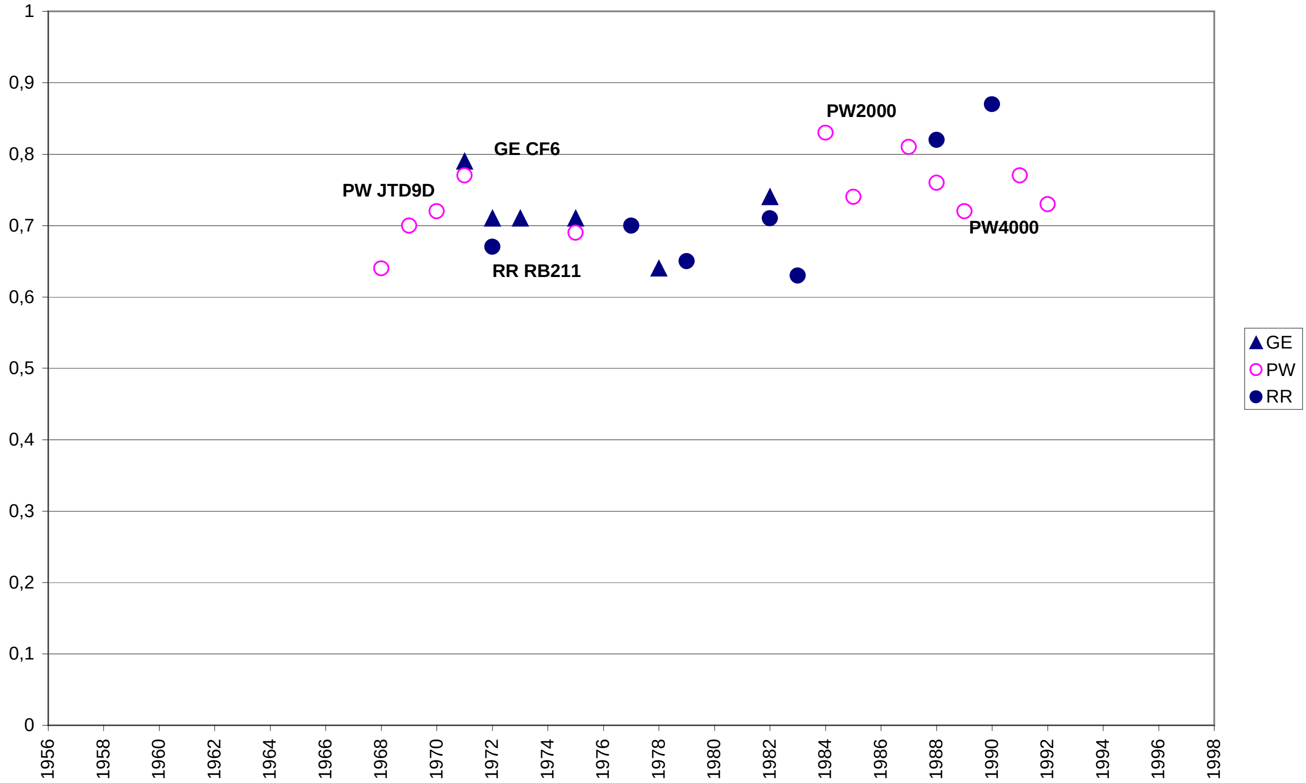

Figure 3 Max DEA efficiency at the firm level, cluster 2

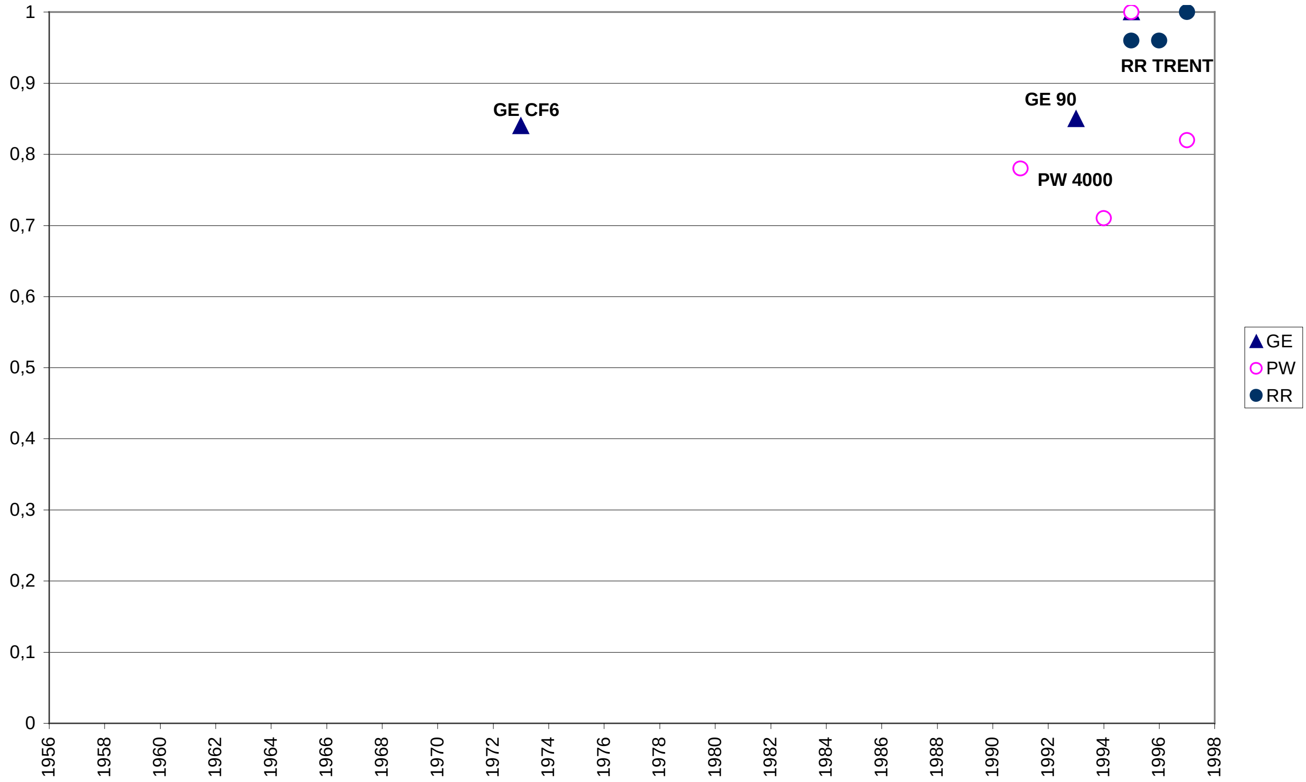

Figure 4 Max DEA efficiency at the firm level, cluster 3

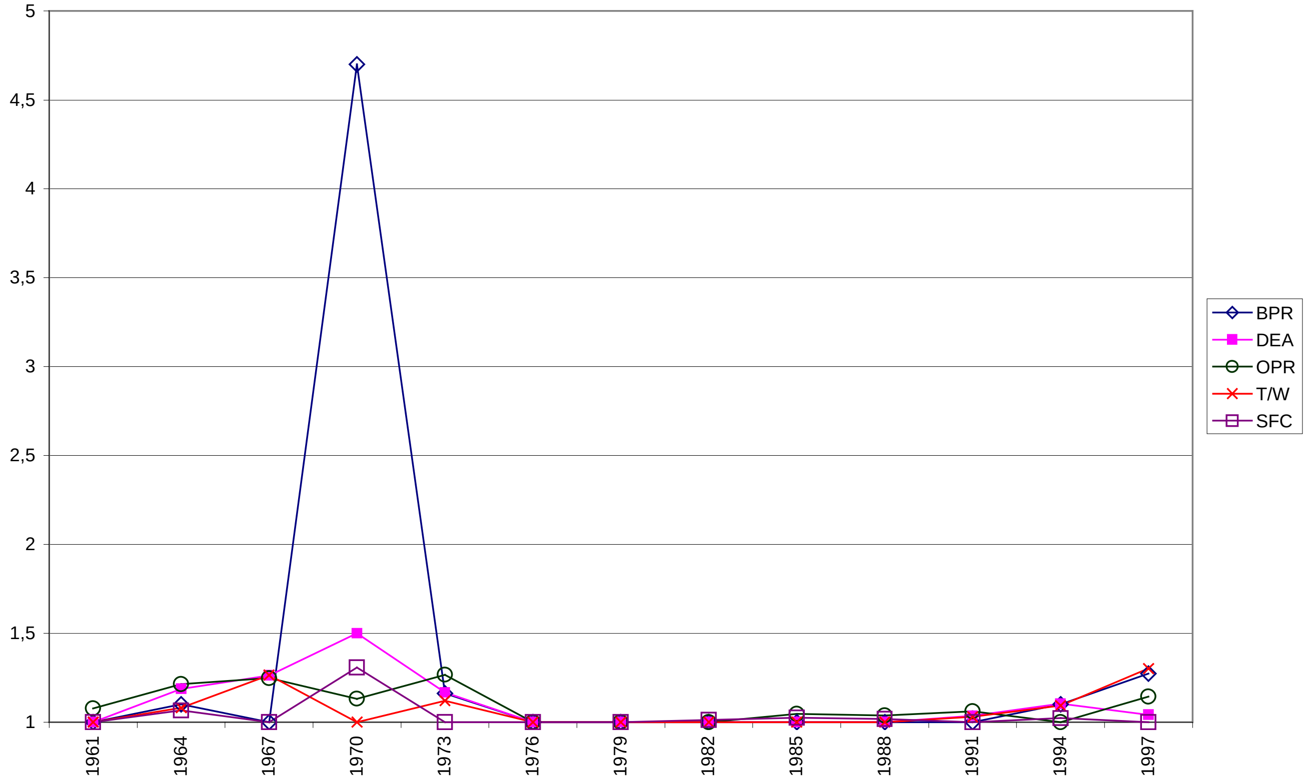

Figure 5 3-years rate of change

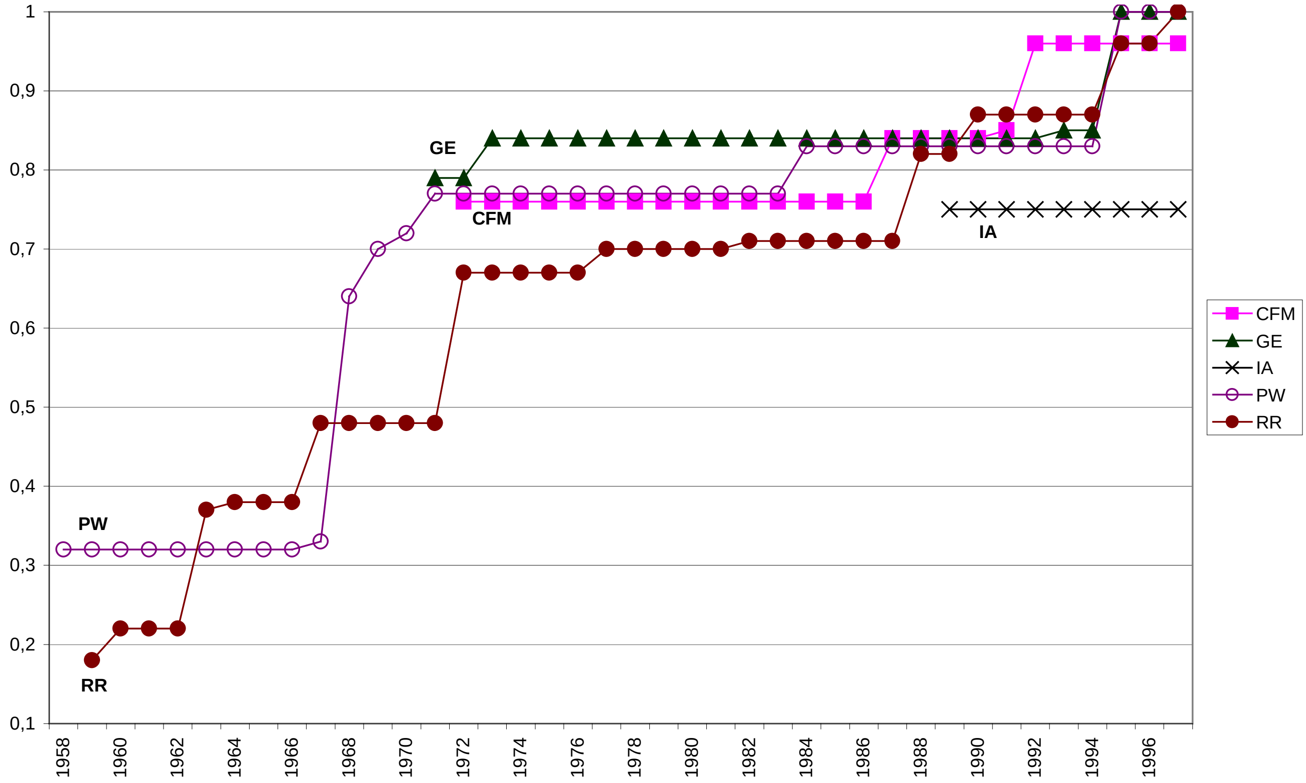

Figure 6 DEA efficiency, technological frontier of larger firms

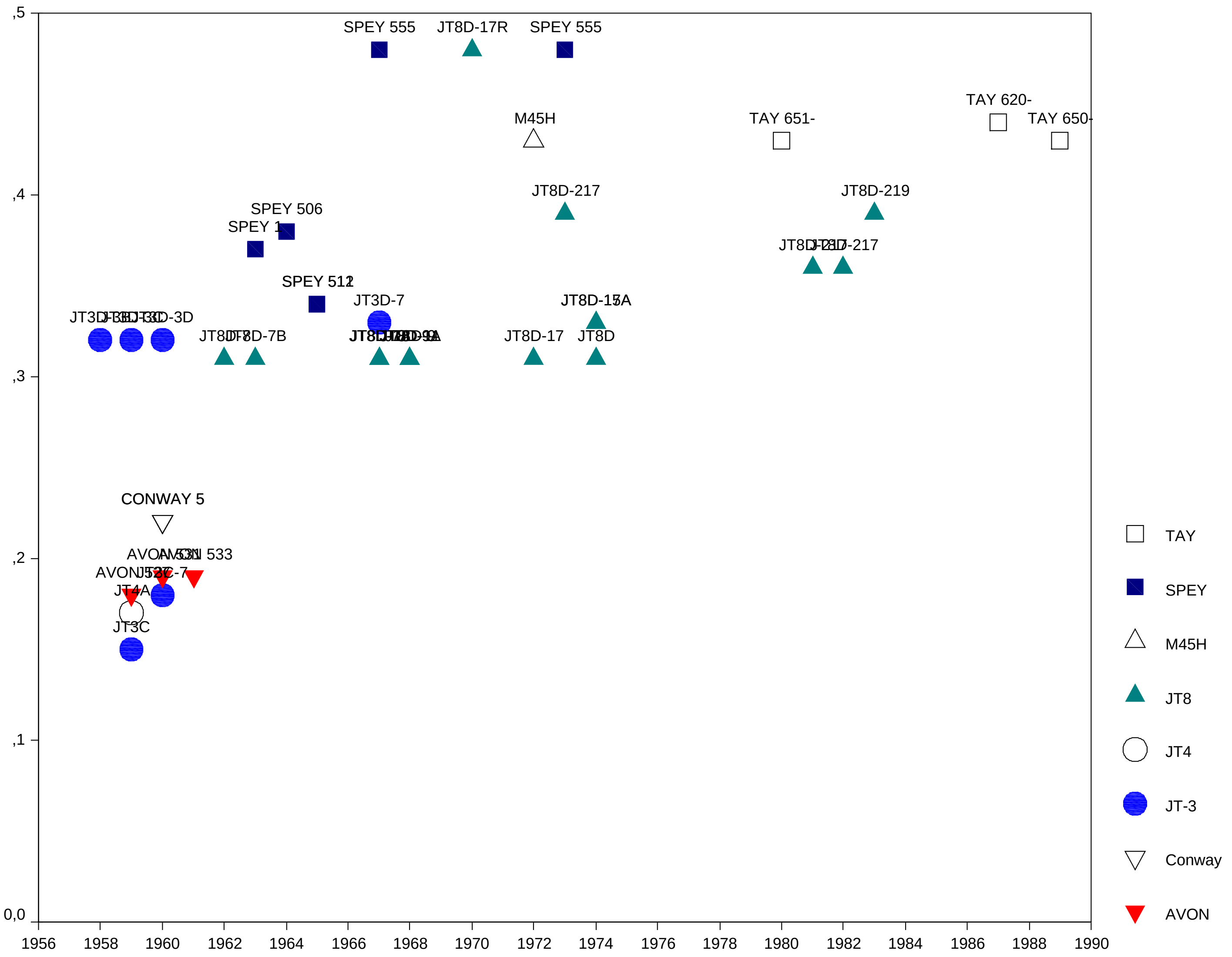

Figure 7a DEA efficiency at the product level, 1

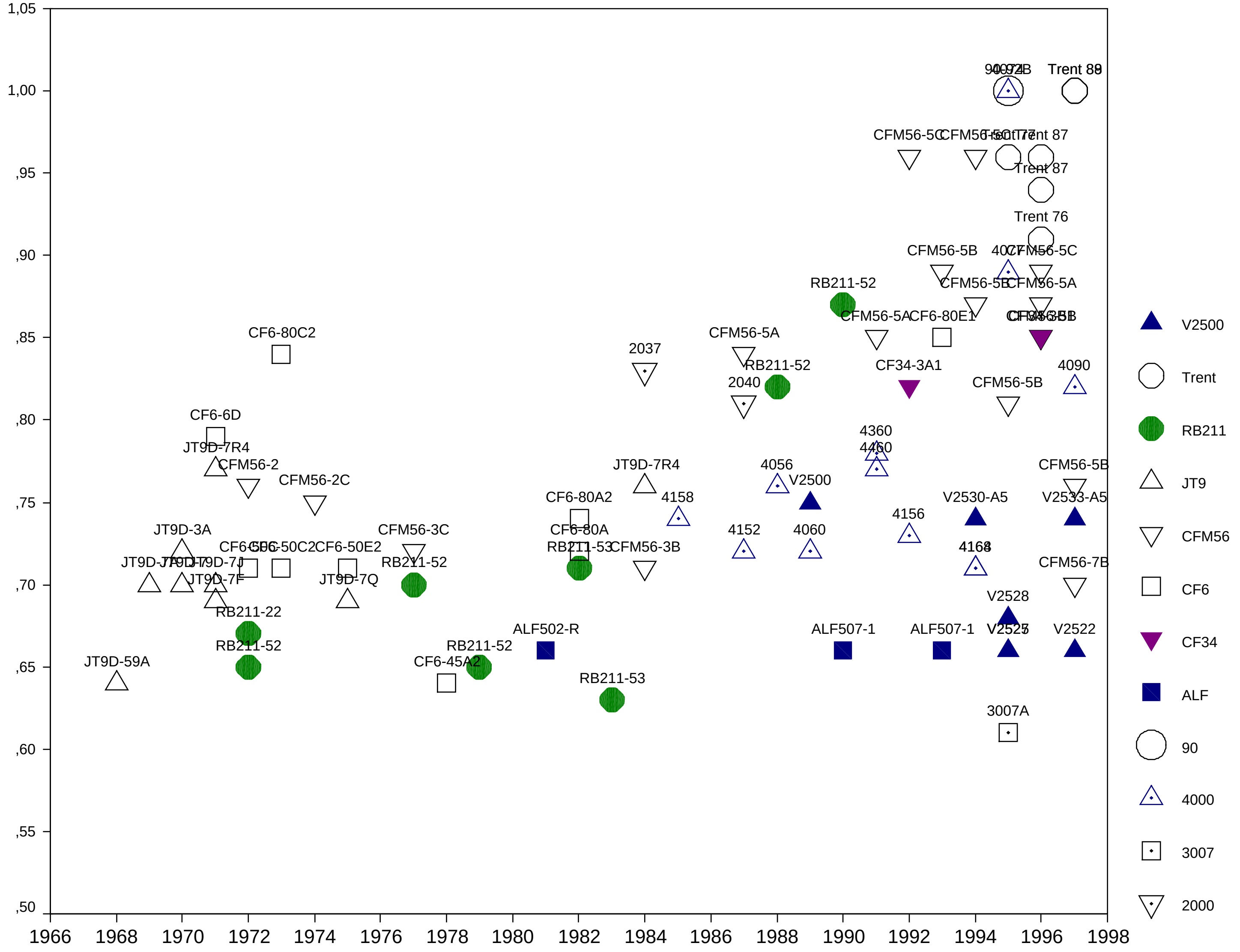

Figure 7b DEA efficiency at the product level, 2

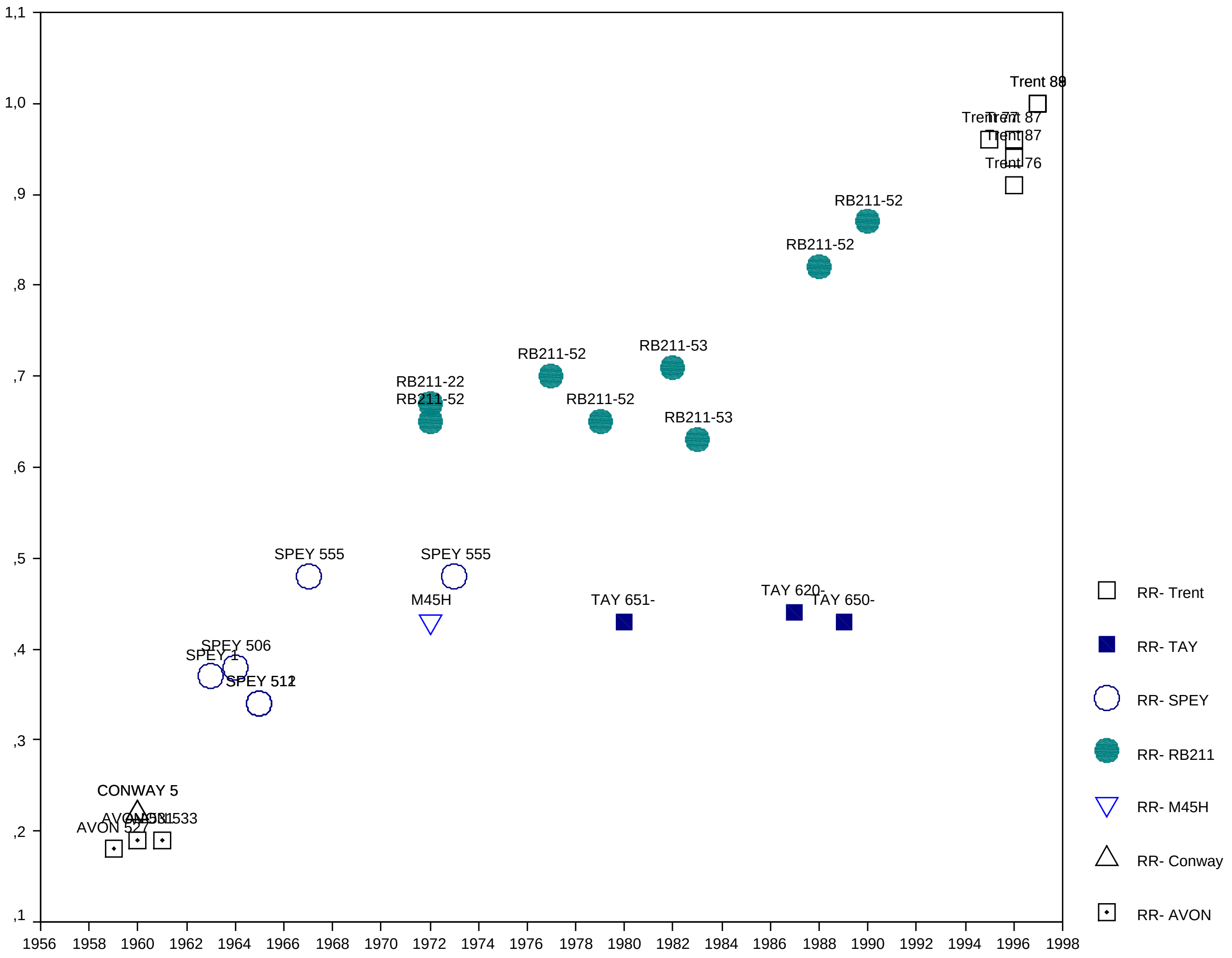

Figure 8 DEA efficiency at the product level, Rolls Royce

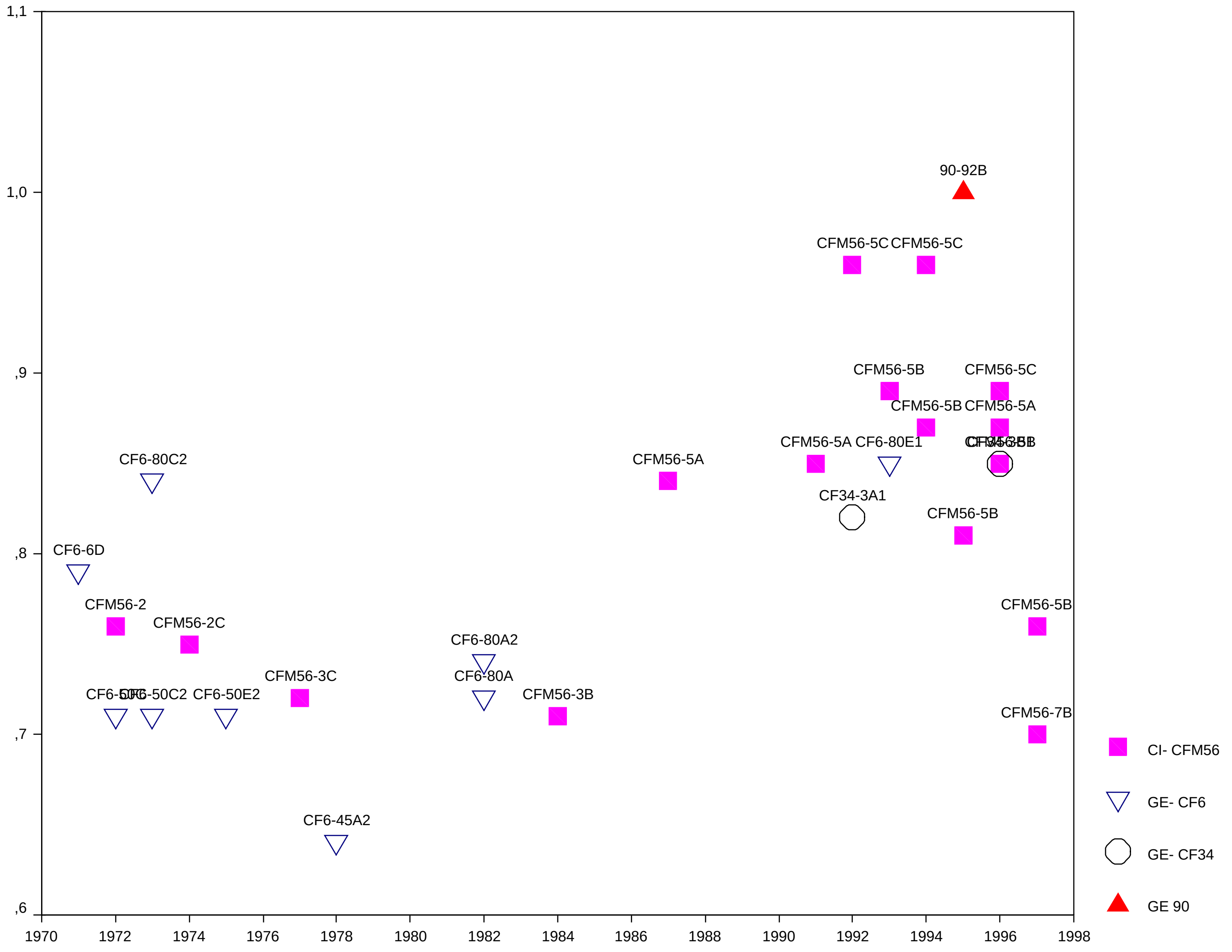

Figure 9 DEA efficiency at the product level, CFM International and General Electric

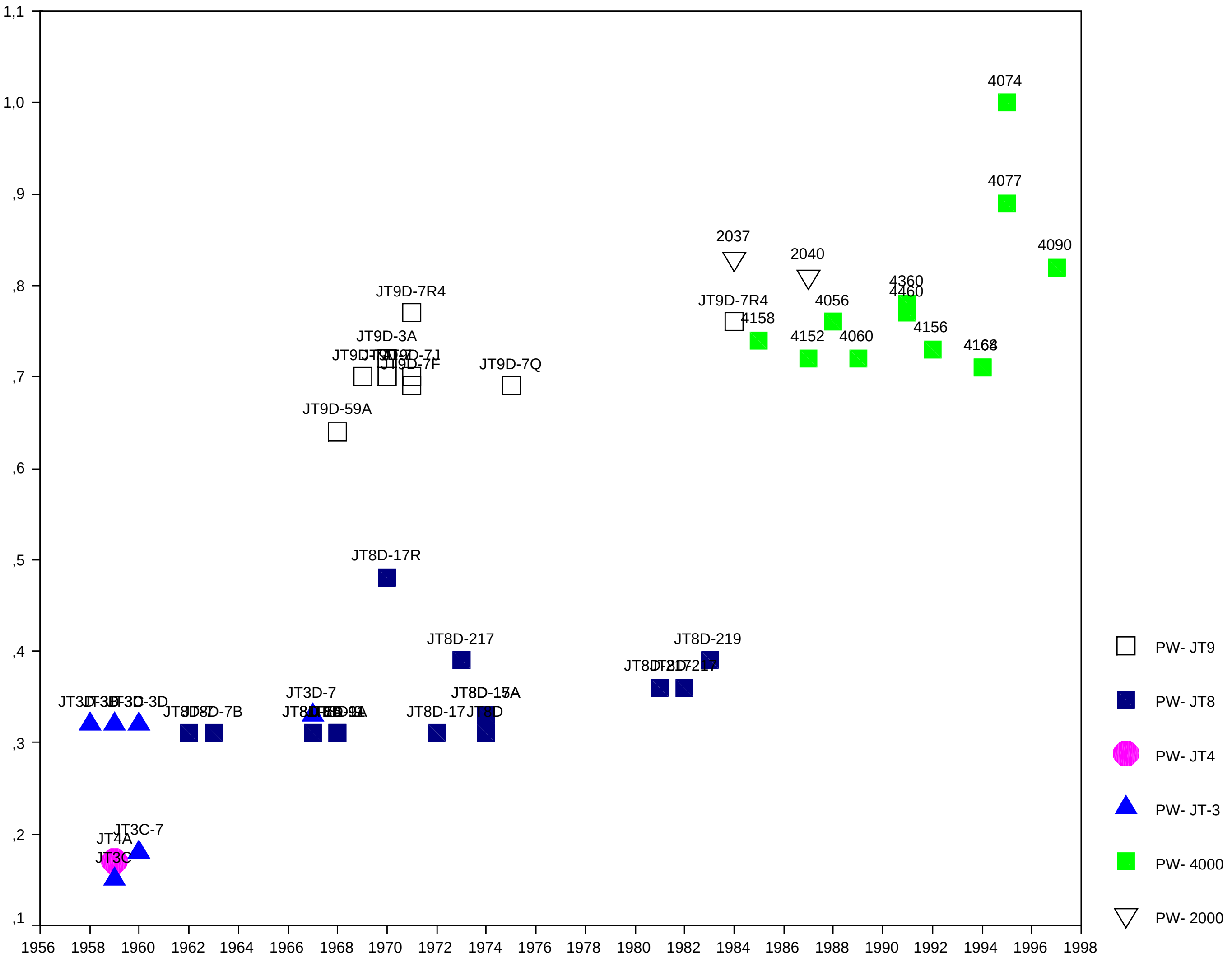

Figure 10 DEA efficiency at the product level, Pratt & Whitney

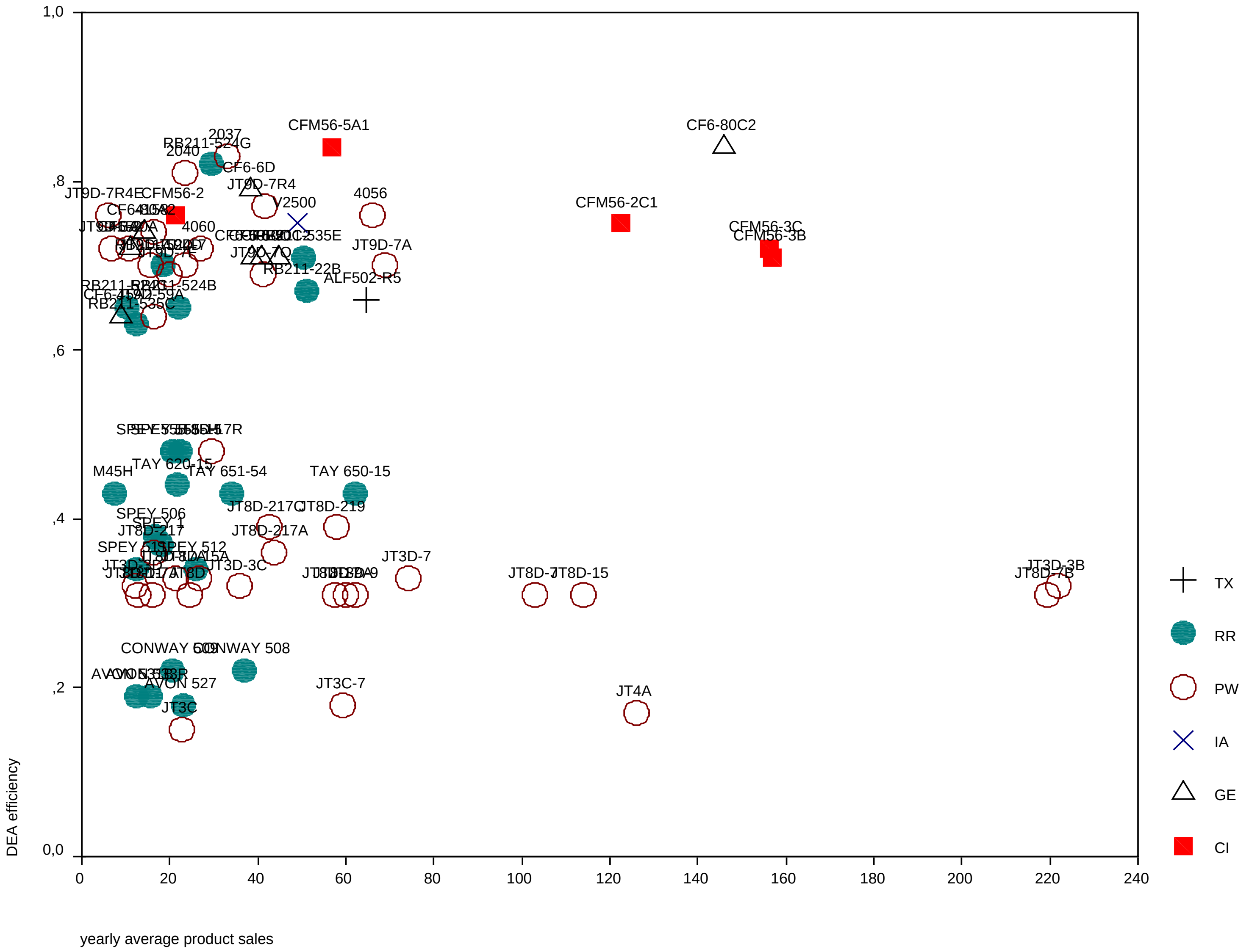

Figure 11 Technical efficiency vs market success