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ENTROPY STATISTICS APPLIED TO AIRPLANE EVOLUTION

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Abstract. *Aeronautical evolution by definition is a technological evolution. As such, like any other form of evolution, it follows certain rules or heuristics. These rules can vary in complexity; from the relatively simple evolution of an arithmetical progression to the more intricate biological evolution of any species, technology belongs somewhere near the complex end of that spectrum. This form of evolution can potentially be lucrative if well understood, especially in the firm level. By employing the entropy statistics methodology, analyses concerning airplane evolution were carried out. The present work is an improved and extended effort regarding the one performed by Frenken and Leydesdorff (1999). Here, proper variables adequately represent the aircraft configuration and its embedded technology. The variables were carefully selected after an extensive study. Both works also differ in range of application. In the present work, two analyses were performed to validate the methodology. One is concerned with the evolution of civil aviation transportation in the jet age (1950-2006) and the other with the evolution of fighter aircraft (1914-2009). A considerable effort was made in order to select the variables used to describe each aircraft. After the creation of the databank, the tool that was developed during this work takes the variables as input to evaluate two important evolutionary indexes: the convergence and the diffusion. Studies analyzing the combination of the diffusion and the convergence indexes, as well as the critical transition of the airplanes were conducted in the present work. A computer tool was also developed, which can be useful in the decision making process in the conceptual design phase of aircraft.*

Keywords *Entropy Statistics, Information Theory, Aircraft design, Conceptual Studies*

Symbols and Abbreviations

WWI	World War One
WWII or WW2	World War Two
MTOW	Maximum Take Off Weight
W/S	Wing Loading
EOW	Empty Operating Weight
T/W	Thrust to Weight Ratio
S	Wing Area
MMO	Maximum Operating Mach Number
C_{Lmax}	Maximum Lift Coefficient
I	Information Content
p_i	*a priori* distribution
qi	*a posteriori* distribution

1. Introduction

1.1. Convergence vs. divergence

It is an amazed experience to observe that the tools and instruments devised by human beings undergo an evolution themselves that is strangely analogous to ordinary evolution, almost as if these artifacts propagated themselves as animals do. Aircraft began as birdlike objects but evolved into fishlike objects for much the same hydrodynamic reasons as those which caused fish to evolve into fishlike objects. Bicycles have evolved and so have motor cars.

The challenge of understanding the dynamics of technological development has long been a concern of every branch of manufacturing enterprises. Two approaches dominates the scene: one suggests that the external requirements of the market (Schmookler, 1966), while the other views the activities and internal capabilities of firms as primary drivers of innovation (Dosi, 1982). Taken in isolation, each approaches highlights key aspects of technological development but, as many have argued, the greatest insight derives from their joint consideration (Movery and Rosenberg, 1979).

Convergence contends that products evolve into unified devices through linear evolutions; whereas divergence disputes this notion, citing innovation is spurred through disruptive revolutions. The Internet was a disruptive technology and the same will certainly occur to the air transportation. A different way to move in the atmosphere will not be called "airplane" anymore.

Convergence captures the imagination, but divergence is tuned to the market. Today many types of aircraft (jet aircraft, propeller-driven airplanes, and helicopters) and many types of automobiles (sedans, convertibles, station wagons, minivans, sport-utility vehicles.) are available. However, no flying car succeeded, although many attempts have been made to bring them into life. Ries (2004) asks the question "Why divergence and not convergence?" According to them, that is because convergence requires compromise and divergence satisfies the evolving needs of different market segments. An automobile needs to be heavy enough to stay on the highway; an airplane needs to be light enough to take off from a runway. No flying car will ever be as drivable as an automobile or as well flyable as an airplane. The autoboat, another convergence concept that has been floating around for decades, suffers from the same flaws.

. The codification of design principles associated with the emergence of a dominant design also implies a convergence of particular design principles that have been developed in the past. Thus, the coming into existence of a scaling trajectory at the industry level is essentially a two-sided phenomenon. It refers both to the diffusion of design principles, and to the convergence of design principles. These phenomena are different: the diffusion of particular design principles does not necessarily imply convergence of design principles, since a design can be scaled in various different and potentially divergent directions. For example, some aircraft firms may scale a dominant design with respect to maximum take-off weight, others with respect to speed, and still others with respect to range. Hence, to test the dominant design hypothesis, one needs to distinguish between the diffusion of design principles through time and the convergence of design principles that can be observed in retrospect.

At this point, it is worthy of mention the different meanings of divergence and diffusion. At first glance, both concepts appear to be the same. Consider the computer. There are supercomputers, network computers, personal computers, laptop computers, tablet computers and handheld computers. That is a typical divergence case, a family of products having the same *common ancestral*. Diffusion is related to different products sharing *common technologies or features*. The fly-by-wire flight and control system appeared in a Western plane in the supersonic Concorde airliner. Since those days, this technology has spread her legs to a large variety of airplanes. Even small to medium capacity airliners like the ENBRAER 170 have adopted such technology. That is a typical example of diffusion.

1.2. Technological evolution modeling

Utterback and Abernathy (1975) have proposed the concept of a product life-cycle to describe technological evolution at the level of an industry. At the start of a product life-cycle, a variety of product designs is being developed. The competition among designs is eventually resolved into a dominant design. Hereafter, innovation concentrates on process and incremental improvement of the product with reference to the dominant design. Nelson and Winter (1977) and Dosi (1982) proposed to describe a series of incremental innovations within a stable design framework as a natural trajectory or technological trajectory, respectively. Along a trajectory, development is guided and constrained by a set of heuristics which make up a technological paradigm. The trajectory concept can be appreciated as the dynamic analogue of the concept of a dominant design.

Nelson and Winter (1977, 1982) and Sahal (1981, 1985) highlighted that trajectories do not only concern periods during which the basic technological principles remain unchanged, but also a stage of incremental scaling of designs. A prime example of a series of scaled models in civil aircraft has been the piston propeller Douglas airliner trajectory. The scaling of the engine power, wing span, and fuselage length have led to improvements in speed by a factor of two, and in maximum take-off weight and range by a factor of five from the introduction of the DC3 in 1936 to that of the DC7 in 1956.

Information theory was first mentioned by Claude E. Shannon in his 1948 paper entitled "A Mathematical Theory of Communication". The main purpose of Shannon's work is to deal with the problem of transmitting information over a noise channel. He could not imagine that a whole new field of mathematics would result from his proposition. Many deep and far reaching mathematical theories were created, such as channel capacity, source-coding and self-information. But Shannon's most important contribution was his use of *entropy* to elaborate most of his theories.

Entropy came into being as *thermodynamic entropy* by Rudolf Clausis in 1850, in his work on Sadi Carnot's 1824 thermodynamic efficiency study. However, the more modern definition of entropy as a measure of "disorder" in a system was introduced by Ludwig Boltzmann in 1877. This "disorder" entropy, or *statistic entropy*, then became the cornerstone of the theory of statistical mechanics and was later used by Shannon in his information theory.

In this context, some textbooks erroneously employ the "student desk increasing disorder with time" as an example of entropy. This can be misleading since the more precise example would be, "which system has higher entropy: the organized desk or the messy one?" The answer would probably be the messy one, because there are many more ways of arranging the items in a chaotic manner than there are in an organized one. This is the Shannon definition of entropy, and the one used in this paper. Interestingly, some scholars today credit Claude Shannon as the actual architect of entropy, since his definition is a much broader one than the original thermodynamic definition, even though it is a much newer concept. These scholars claim that thermodynamic entropy is a category of information entropy.

How does this statistical entropy relate to the study of technological evolution? Any system that contains a macroscopic state ruled by many different microscopic systems, such as biological evolution, economic growth, image reconstruction and technological evolution; can be studied using entropy.

If a certain technology has established itself over a long period of time without any major breakthroughs, one can conclude that the entropy of that particular era is very low, since there is a low degree of uncertainty. This means that some major breakthrough has occurred in the past and that most of the competitors, if there are any, have borrowed information from that breakthrough. The appearance of a dominant design usually precludes a low entropy era, while an era of experimentation, with high diversity shows no dominant designs, and thus, high entropy.

Therefore, one can use these far reaching theories to study the evolution of technology in a specific sector of industry, such as civil aviation, automobiles, computers, etc. In this study we will analyze the evolution of civil transport aviation of the jet age (1950-2006) and the evolution of fighter aircraft of the 20th century (1914-2009) by using some specific points from information theory and entropy statistics, discussed in the next section. Although many calculations are performed in this analysis, the results can only be interpreted in a qualitative manner. Entropy statistics is best employed, outside of pure information theory and thermodynamics, as a tool for qualitative analysis of a subject.

2. Methodology

A previous work on this subject, written by Frenken and Leydesdorff (1999), will be used as the baseline methodology for the present study. The targeted improvements are the choice of variables for each design, the availability of newer design data and the focus on Embraer airliners, while conducting firm-level analysis. Another expected conclusion for this work is to ascertain how robust the applied theory and methodology really is in this case.

2.1. Data structure

The most effective way to numerically represent a product is to model its various trade-offs, since these are the expression of years of technical development for a product. To model these trade-offs it is necessary to create ratios between every characteristic of a product. Arranging these ratios in matrix form creates a model of the trade-offs. This matrix is a good numerical representation of a product design, but it is not useful in information theory.

Dividing theses ratios by the sum of all the ratios creates a probabilistic distribution ($p_1, p_2, \ldots, p_n \rightarrow$ where n is the total number of ratios). This is called a probabilistic representation for each product and will be used for every calculation in this procedure.

Every product contains some information from previous designs and provides information to future ones. Using information theory we can calculate how much information is passed among designs using the formula below:

$$I(q \mid p) = \sum_{i=1}^{n} q_i \log_2 \left(\frac{q_i}{p_i} \right)_i \qquad (1)$$

Where I is the information-theoretical distance between two product designs, where q is chronologically after p. This is the same as the amount of information passed on from p to q. If no information was passed than I equals zero, because every trade-off is the same, even if the characteristics are not the same. This would be a perfectly scaled version of a previous product. Mathematically this means that $\left(\frac{q_i}{p_i} \right) = 1$ and its log is zero. Interestingly no matter what I is, it will always be positive, this is called probabilistic entropy, and it is due to the fact that every message that change has occurred is expected to contain information.

Lower I means less change has occurred from p to q, in other words, the more similar two products are and vice versa.

After an extensive analysis, some parameters representing the characteristics for the entropy analysis were selected. They are described below and listed according to the aircraft categories under consideration

Airliner

1. Thrust to weight ratio (T/W);
2. Empty to gross weight ratio (EOW/MTOW);
3. Payload to gross weight ratio;
4. Fuel per Passenger Mile [kg/nm];
5. Maximum operating Mach number (MMO);
6. Range with max. payload [nm];
7. Maximum lift coefficient (C_{Lmax});
8. Service ceiling [ft];
9. Wing loading (W/S) [kg/m^2]

Fighter aircraft

1. Wing span [m];
2. Total length [m];
3. Total height [m];
4. Wing area (S) [m^2];
5. Empty weight [kg];
6. Maximum take Off Weight (MTOW) [kg];
7. Maximum speed (VMAX)[km/h];
8. Service ceiling [m];
9. Range [km];
10. Full armament payload coefficient [mm + kg];
11. Thrust to weight ratio (T/W);
12. Wing loading (W/S) [kg/m^2]

In fact, other important parameters shall be taken into account for the calculations. One of them is the lift-to-drag ratio. However, lack of reliable source of information led the authors to drop out some parameters. Further work will take into account them by a more intensive search in the available literature. The computer code that was developed in the present work is able do analyze the evolution of any kind of object. However, the object of the investigation is technological evolution of aircraft. The first step is to gather enough data for the calculations. This is one of the only limitations of the method. It requires dozens of data points to produce an effective and useable result. Naturally, the most important information for each product is its initial service date, without it there can be no study.

2.2. Diffusion and Convergence Values

In the industry level, a certain design may be compared with its successors or predecessors in order to gauge its effect on the competition, for a certain period. A dominant design is one that has a high degree of diffusion of its design into subsequent products, and also one that includes a high degree of convergence of previous design principles into it. Mathematically, this is accomplished by, first, selecting an appropriate time scale to be used, for the civil aviation five years works well. Take a specific product, for diffusion; calculate the average I-values for each product in the succeeding time period. For convergence, calculate the average I-values for each product in the preceding time period. Doing this for every product in the database creates a time based plot of diffusion and convergence I-values. The lower the I, for both diffusion and convergence, the closer a design is to a dominant one for its time.

2.3. Critical Transition

When comparing three designs in chronological order (A→B→C), the information-theoretical distance between all them can be determined. In normal Euclidean space the distance between A and C will be smaller or equal to the sum of the A and B and B and C distances. However, the information-theoretical distance between A and C can be bigger than the sum of the smaller distances. This means that design B has caused enough impact on C and has a lot of influence from A that the information-theoretical distance is smaller. When this happens, the design process A through B through C is called a critical transition, and it is a safe bet that design B is a major success and the following designs are scaled designs. In other words, one can think of design B as a catalyst or amplifier. A firm that creates a product with the characteristics of design B will be able to leap forward in technology faster than its competitors.

$$I(B \mid A) + I(C \mid B) < I(C \mid A) \tag{2.1}$$

$$I(B \mid A) + I(C \mid B) - I(C \mid A) < 0 \tag{2.2}$$

3. Results

3.1. Commercial airline transportation in the Jet Age

One of the more unusual aspects of the coming of the jet era was the speed with which airlines internationally adopted these new aircraft. Partly because of Pan American's example, airlines from all over the world replaced piston-engine aircraft with jets at an unprecedented pace. The Soviet national airline Aeroflot was part of this explosion. In fact, Aeroflot held the distinction of offering the world's first regularly scheduled and sustained passenger jet service with its Tupolev Tu-104 aircraft. Aeroflot opened service from Moscow to Irkutsk in September 1956. The second jet revolution came into life in the 90s even speedier than the previous one. It ook place after Embraer and Bombardier Aerospace (former Canadair) introduced their regional jet seating 50 passengers. The so-called regional jet replaced turboprop aircraft in many routes. However, their most importation contribution for the aviation was the opening of new routes, with some of then enduring 3 hours or more. The main reason for the success of the regional airlines was their intrinsically low-cost structure.

3.1.1 Diffusion and Convergence Analysis

After calculating the diffusion and convergence values for each aircraft in the airliner database, they were plotted on a time scale and also plotted against each other.

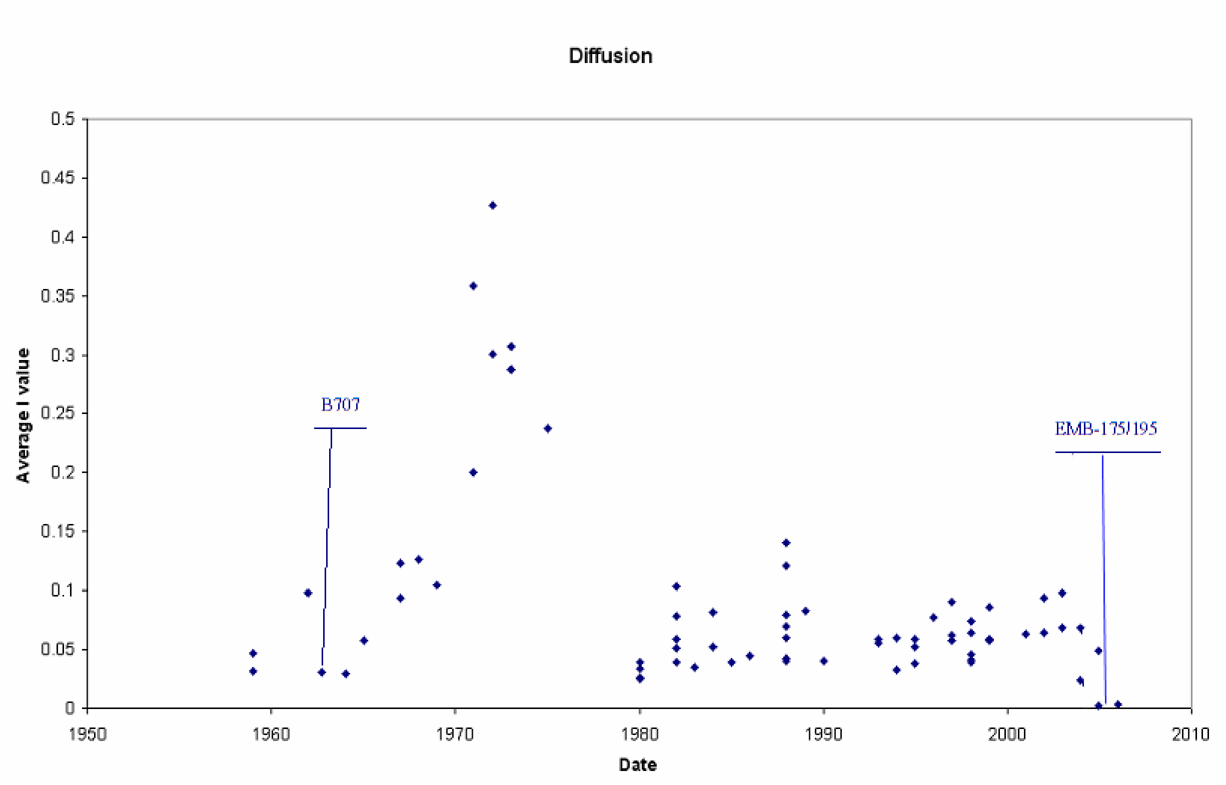

Figure 1 - Diffusion I-values for airliners in the Jet Age.

On the diffusion plot **Figure 1** one can see that the lower I-values (meaning more diffusion) are concentrate after 1980, and that before that higher values (less diffusion) were more common. Studying the history of commercial transport aircraft it is possible to determine the explanation for this occurrence. In the early jet age, all of the designs were breakthroughs from their propeller predecessors. Therefore, a high degree of diffusion of their design principles can be observed because all of the subsequent aircraft were based solely on these pioneers. Observe the low values for Boeing 707 (0.0982), Sud-Aviation Caravelle (0.0465), and Douglas DC-8 (0.0315). As the technology matured, however, firms started experimenting with new design configurations - this can be seen in the early to mid-70s. The tri-reactor series of aircraft are all included in this era, and none can be seen flying nowadays, McDonnell Douglas DC-10 (0.358), Boeing 727-200(0.200) and Lockheed Tristar (0.307). The same can be said about the supersonic aircraft like Concorde (1.204). The supersonic airliner Concorde is not shown in the graph because it dwarfed the other values. The twin-pusher CBA-123 turboprop (1.224) – a commuter plane for 19 passengers - shows high values and fits the above description. Since the A380 (1.056) has just recently flown it also shows high values, because it is very different from the aircraft it was compared to others that flew recently. After the 1980's the diffusion average drops significantly, this shows the emergence of a dominant aircraft configuration, which is a low wing, high flying, twin turbofan aircraft. Among these are Boeing 767, Airbus A320 and that from Embraer, all of them with high diffusion. Still in diffusion it is interesting to note the extremely low I-values for the EMBRAER 175 – referred to as EMB-175 - (0.00307) and EMBRAER 190 – mentioned as EMB-190 - (0.0025). This can be partially explained by the fact that only these airliners present an entry into service date of year 2005. Additionally, they are scaled versions of each other, and mainly of the EMBRAER 170, which is referred to as EMB-170. The EMB-170 (0.0242) also has a low value, but higher than its bigger companions because it compares with the A380 as well, as a 2004 airplane.

Figure 2 was leased from Frenken's work and is used here for comparison reasons. There is a good matching when the results presented in **Figure 1**. That indicates the robustness of the method, especially with a solid calculation tool such as the one developed for this work. It is important to mention that Frenken's work covered airliners from 1927 to 1997.

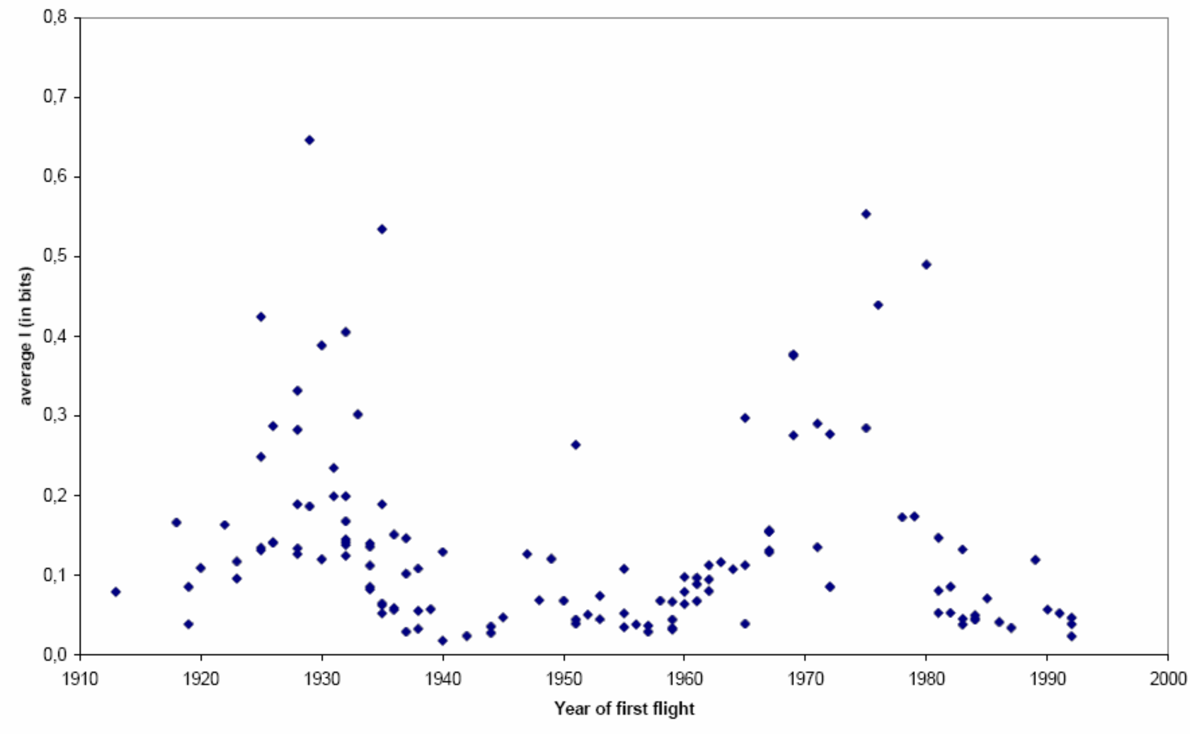

Figure 2 - Diffusion I-value for Civil Air Transport (Frenken).

The same overall behavior of convergence graph can be seen on the diffusion one (**Figure 3)**. In this case, it can be stated that the aircraft designed after the first jet transports show a high convergence of design principles, as can be seen as a small dip in the I-values for the Douglas DC-9-30 twinjet (0.0327), as well as for the DC-9-40 variant (0.0156) and Boeing 747-100 (0.0420). The same rise in I-values on the diffusion graph can also be observed, except this time it occurs about five years later than on the diffusion. This is also mainly due to the major failures like the Concorde (0.902) and the CBA-123 (0.498). The A380 (0.750) presents again high values, but this is due to the fact that it uses little information from previous designs, mainly due to its ultra-large dimensions. If, in the future, the A380's diffusion values lowers it will become a monopoly much like the 747 in its day.

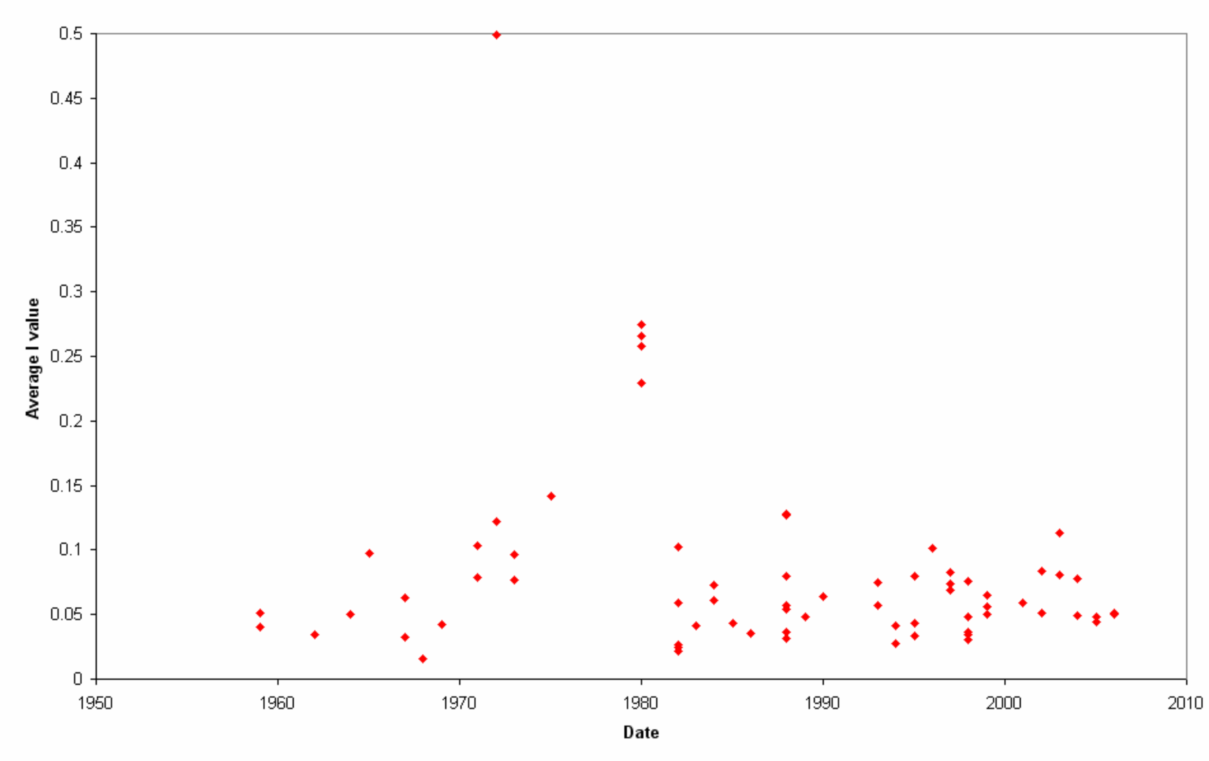

Figure 3 - Convergence I-values for airliners in the Jet Age.

Following the spike, all of the aircraft show a high degree of convergence from previous designs, just as with the diffusion plot. When compared to Frenken's work. **Figure 4** reveals that the similarities are very tight. Even considering the slightly different for some I-values between both works, most aircraft present the same I-values in the graph. Once more, the strength and robustness of the method was accomplished.

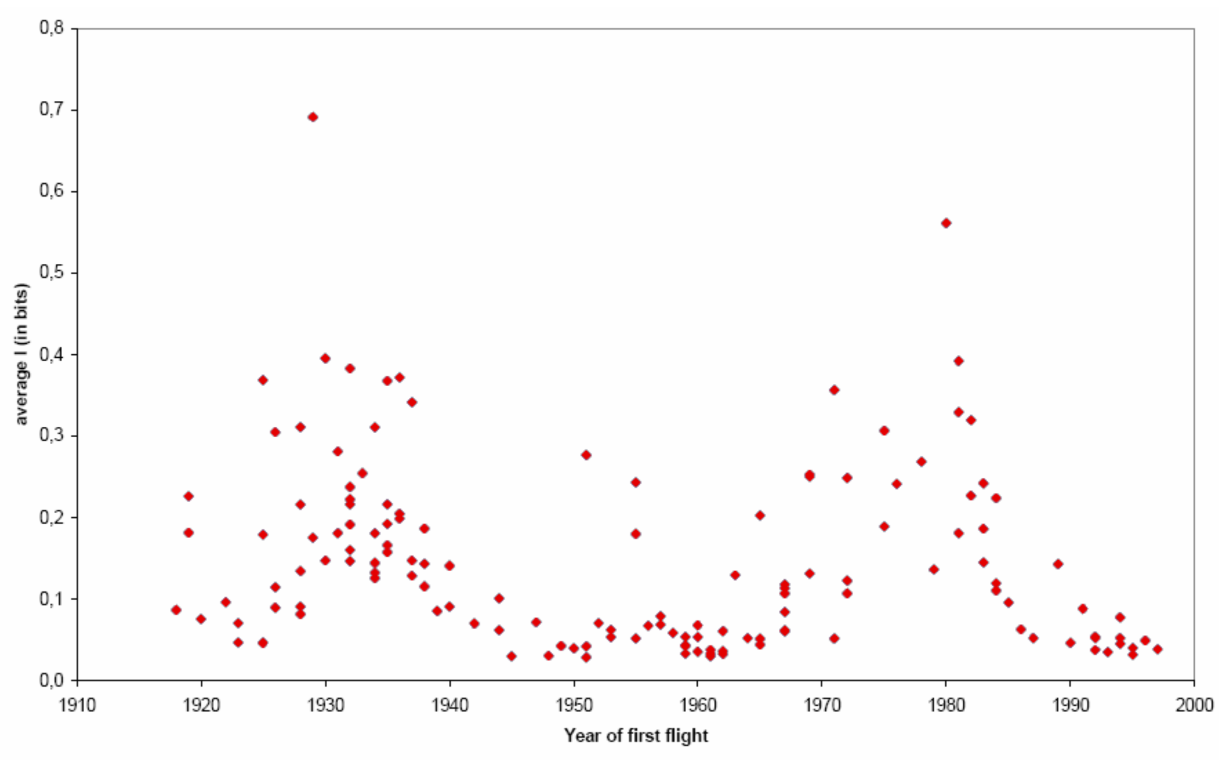

Figure 4 - Convergence I-value for airliners according to Frenken's work.

The last graph in this section is used as an illustrated guide for distinguishing types of innovation. In his paper, Frenken (1999) classifies four types of innovation (**Table I**). In **Figure 5**, it can easily be observed where each aircraft falls within that classification. The SST (Supersonic Transport - Concorde) and the CBA-123 are both failed designs according to the present calculations (high I-values). Even taken into account the Concorde flew for many years as the sole SST. While the McDonnell Douglas DC-10 trijet and Boeing 747 fall into the monopoly category, because of their extra widebody status, they had a lot of influence from previous designs but their influence on later designs was, as is well known, very small. In this study the MD-80 aircraft series reveal themselves as a breakthrough design. This makes sense since they were the first successful mid-range high-bypass turbofan aircraft, their influence on later designs like Fokker 100/70 and the ERJ 145 aircraft family.

Convergence	**High I-values**	Breakthroughs	Failures
	Low I-values	Dominant Designs	Niche, Monopolies
		Low I-values	**High I-values**
		Diffusion	

Table I – Design categories.

The dominant design for the new era of civil aviation transport, according to this study is the EMBRAER 170 family of aircraft. They are the last in a long line of scaled aircraft capitalizing on a sound design and improving on it incrementally to attend market needs. The EMBRAER 170/175 airliners revolutionized the market segment that they are target for. Presenting engines below the wings they enable shorter turnaround times on the ground proving this way a increased daily utilization rate. Besides, their unique cabin dimensions care for a superior comfort and can be compared to widebody revolution pioneered by Airbus in the 70s for the segment of larger capacity.

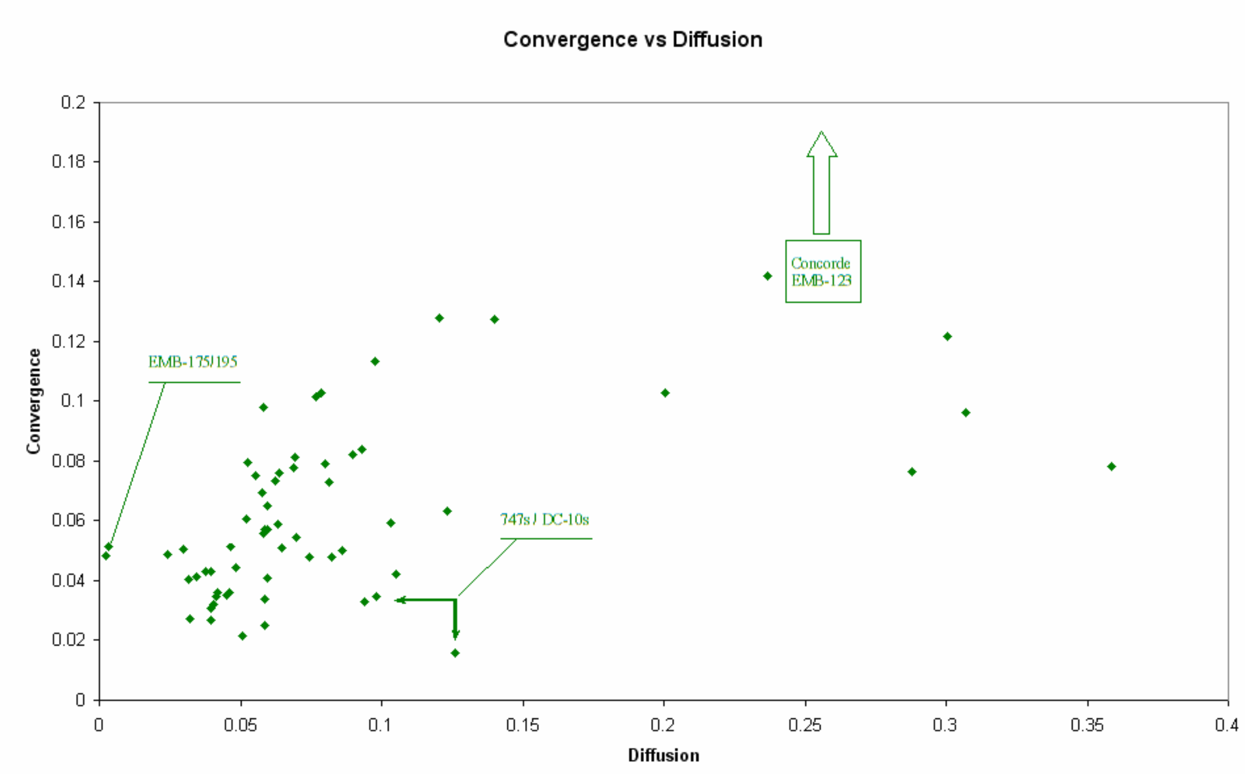

Figure 5 - Diffusion and Convergence for Civil Air Transport in the Jet Age

3.1.2.Critical Transition Analysis for EMBRAER Aircraft

In order to analyze Embraer aircraft evolution we use the critical transition method described in the **Introduction**. This is interesting when considering that Embraer has evolved from the unpressurized EMB-110 Bandeirante twin turboprop, to the ultra-modern EMBRAER 195 airliner (referred to as EMB-195 in Graphs and Tables). The aircraft were used in chronological order as required by this method.

Group	Aircraft Analyzed	Distance
1	EMB-110 -> EMB-120 -> EMB-123	0.0908
2	EMB-120 -> EMB-123 -> EMB-145	0.1119
3	EMB-123 -> EMB-145 -> EMB-135	0.0575
4	EMB-145 -> EMB-135 -> EMB-140	0.0185
5	EMB-135 -> EMB-140 -> EMB-170	-0.0163
6	EMB-140 -> EMB-170 -> EMB-175	-0.0046
7	EMB-170 -> EMB-175 -> EMB-190	-0.0035
8	EMB-175 -> EMB-190 -> EMB-195	-0.0011

Table II - Critical Transition for EMBRAER Aircraft

In **Table II**, the ERJ 145 twinjet is mentioned as EMB-145 and the CBA-123 turboprop is referred to as EMB-123. The value of 0.1119 for the distance related to the Group # 2 is in the spotlight. This result can be explained by the fact that the CBA-123 was a commercial failure, because of the cutting-edge technology that it featured. But even more interesting is the fact that the last for transitions were all considered critical ones. This proves the fact that the EMBRAER 170/190 family of aircraft is destined to become a dominant design in the near future, evidence of that the analyses indicated for the ill-fated Bombardier C-series.

3.2 Results Interpretation for Fighter Aircraft (1914-2009)

3.2.1. Diffusion and Convergence Analysis

The same methodology employed for airliners found an application here. However, there are some differences, which will help to evaluate the robustness of the codification and methodology. First, the number of designs in the fighter databank was considerably larger than that contained in the airliner one: 235 instead of only 74. The number of parameters to model the plane characteristics was also increased from 9 to 13 instead. Considering that the code did not need to be rewritten throughout the analyses indicates that it can handle any type of data, as long as the proper format is provided.

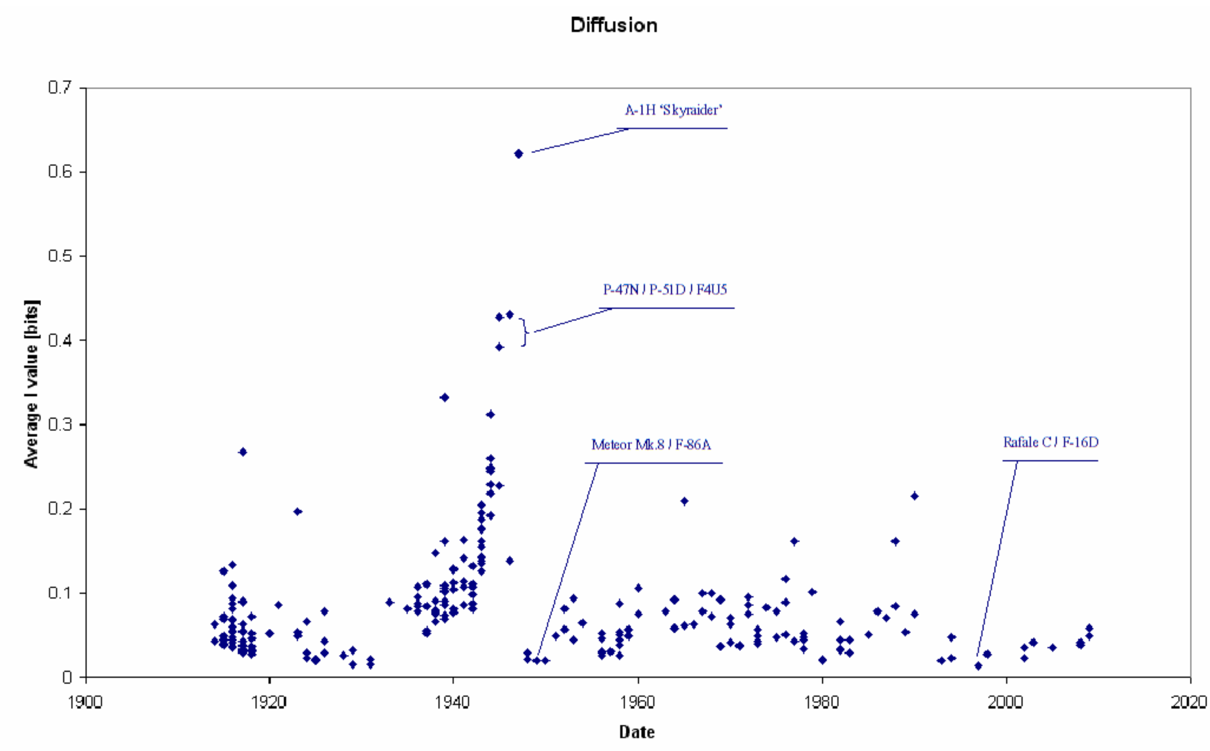

Figure 6 - Diffusion I-values for Fighter Aircraft.

The analysis revealed some important departures regarding the previous study on the commercial aviation. The first difference can be seen in the diffusion graph, shown in **Figure 6**. It can be observed the effects that WWI (1914-1918) and WWII (1939-1945) exerted on fighter design. The very stringent requirements that emerged during those wars tremendously accelerated aircraft development. These periods present a substantial rise in I-values, translating a high degree of diffusion - more pronounced in WWII. This shows that competing countries and firms were producing very different designs, no dominant design is apparent. In WWI it is less visible, however, since it is the beginning of aviation, there isn't much one design can differ from another. After WWII the mean I-value seems to lower as a result of constant technological evolution and also some dominant designs. At the last decade there is a dip in I-values, this shows the presence of a dominant design. The Rafale (0.0135) and the F-16D (0.0193) seem to be the likely candidates.

Many aircraft presented a low degree of diffusion (high I-value) into subsequent designs. This is the case for the A-1H Skyraider (0.621), one of the last piston-powered fighter/attack aircraft developed in WWII. Because it is the last one of its kind, it not diffused its technology onto later designs. Developed to satisfy a US Navy requirement of 1944 for a single-seat carrier-based dive bomber and torpedo carrier, the Douglas AD Skyraider materialized too late for operational service in World War II. Ordered into production alongside the Martin AM Mauler, which has been developed to meet the same specification, it was to continue in production until 1957. The Skyraider reflected the navy's wartime experience gained in the Pacific theatre, where it had been proved that the most important requirement for such aircraft was the ability to carry and deliver a heavy load of assorted weapons. Of low-wing monoplane configuration, a big Wright R-3350 radial engine was selected as the most suitable power to meet the load-carrying requirement, and this more or less dictated the fuselage proportions. The prototype XBT2D-1 flew for the first time on 18 March 1945. When production terminated 3,180 aircraft had been built in many variants. The Skyraider was also employed in the anticipated early warning (AEW) role. Facing with Kamikaze threat during 1944 the United States Navy started the development of an airborne radar system in order to expand the radar horizon under which the Fleet was to operate during the series of campaigns through the Philippines and northwards to Japan. For this reason, the AN/APS-20 radar as fitted to the TBM-3W and PB-1W became the mainstay of AEW aircraft developments following World War Two. While not designed specifically as an AEW aircraft, the Grumman AF-2W Guardian, when fitted with the AN/APS-20 had a secondary capability endowed by this system. Experience with the Guardian led to the development of an AEW variant of Douglas Skyraider. Once again the radar chosen was the AN/APS-20, with a large belly radome being fitted and a crew of three (one pilot and two operators) being carried. The Skyraider AEW was built in three versions, the AD-3W, AD-4W, and AD-5W. AEW aircraft is another example of divergence.

Most of the late propeller fighter designs have low diffusion, P-47N (0.427) F4-U5 (0.4305) and the P-51D (0.311), this also makes sense since they had not much in common with the jets that were being developed at their era. Other corner of the diffusion spectrum is inhabited by some early jets, such as the Meteor Mk.8 (0.020) and the F-86A (0.021). This is likely explained by the fact that a lot of their technology was passed on to later designs. One could expect such aircraft as the P-80 (0.248) and the Me-262 (0.227) to be in this category, but this is not the case because as the pioneers most of their design ideas were not carried through, and the second generation is probably the one that contains the 'good' decisions. This is the price to pay for a breakthrough technology.

Figure 7 - The first early-warning and Control (AEW&C) aircraft of WWII. From left to right: AF-2W Guardian, Grumman TBM-3W Avenger and Douglas EA-1E Skyraider.

The convergence plot, as seen in **Figure 8**, shows the same overall tendency seen in the diffusion figure. The same high I-values during the wars are observed. The main difference here is the fact that the high I-values do not lower as much after the conflicts, especially after WWII, or the birth of the jet age. During the Cold War (1950s-1980s) there is a higher mean as opposed to the diffusion values, this is probably because there are many minor breakthrough designs in this era.

Note, also, that the convergence I-values during WWII are lower than the diffusion ones. This was expected considering that a war boosts technological advances with a great emphasis on improving existing ones. Another factor that contributes to this phenomenon is the invention of the jet engine during the same war, which raises the diffusion I-values. The lower convergence aircraft (high I-values) for these fighters are the P-80C Shooting Star (0.451), the MiG-15 (0.457), the Meteor Mk.8 (0.422), the F-86A (0.362) and the Me-262 (0.393). These are some of the early jet fighters, mostly second generation. This low convergence represents the great leap from the propeller to the jet in air combat, in other words, very little information was passed on to these designs.

The high convergence area is populated by some very old designs, like the P-36 'Peashooter' (0.017) and the Fokker DXXI (0.023) two of the last of the pre-WWII designs. There are some newer fighters as well, the Rafale (0.014), the Chendgu J-10 (0.015) and the F-16C (0.025). All of these fighters have many common design characteristics, they are all light, limited range, very maneuverable aircraft.

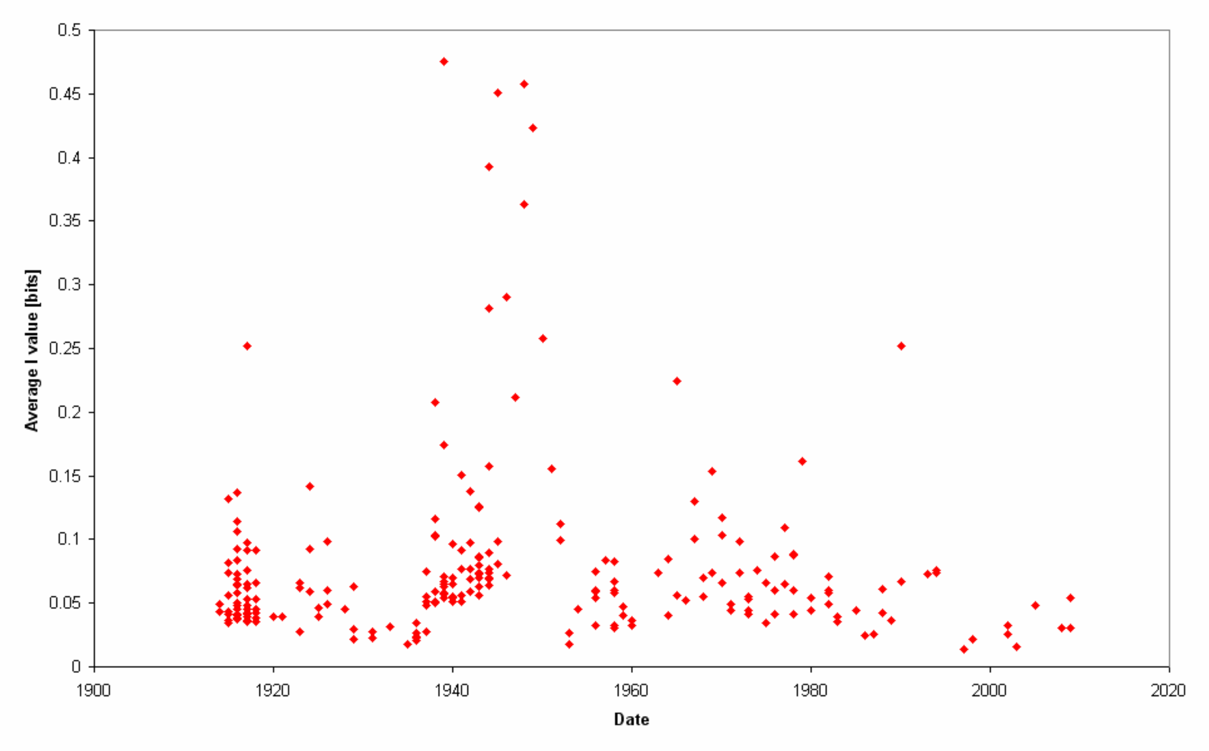

Figure 8 - Convergence I-values for Fighter Aircraft

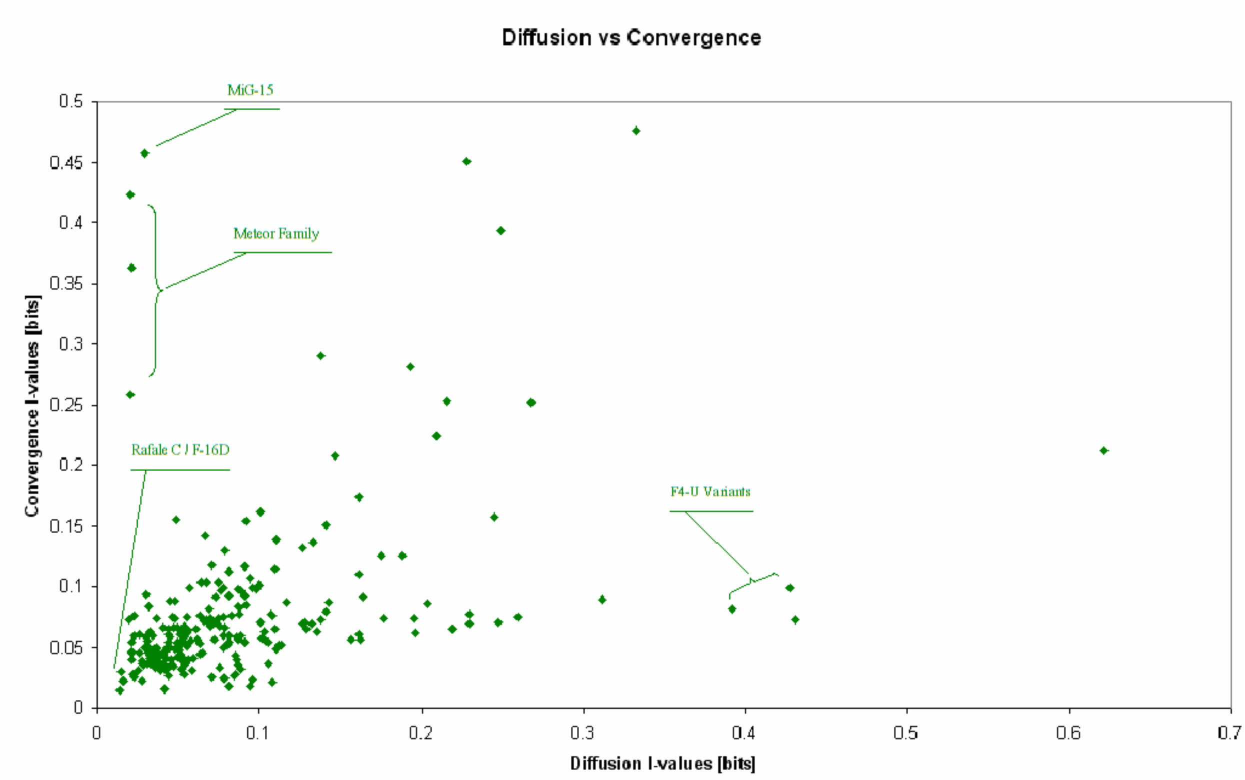

Figure 9 - Diffusion and convergence for fighter aircraft.

Figure 9 displays the combined diffusion/convergence. Using the same classification technique of **Table I**. we can categorize some aircraft. For example, the MiG-15 is undoubtedly one of the major breakthroughs of the early jet age, and it is proven because it shows low convergence and high diffusion. The Meteor variants are all in the same classification as breakthroughs. Now, the F4-U Corsair variants fall into the niche/monopoly category, since they were by far the most advanced carrier based fighter aircraft of their time, and also the last ones, they can be found in the low diffusion, high convergence area of the graph (lower right quadrant).

Some dominant designs, as was mentioned earlier in this section, are the Rafale C for the modern fighter jet, the F8-U Crusader for the Cold War fighters, the Bristol Bulldog for the pre-WWII era, and the Albatross D.III for WWI (not a very dominant design, but considering the effects of war, it is one nonetheless). During WWII no aircraft stands out as a dominant design, due to the high entropy encountered during that period.

4. Concluding Remarks

It was shown that by combining a seemingly unconnected mathematical theory and an empirical study of technological development one can create a very useful qualitative analysis tool. This tool can be used as a technology study aid, in an academic setting, or as part of a firm's decision making process.

As an academic tool, it is very interesting to use it with a variety of seemingly unrelated products in order to study the effects of major events and breakthroughs on the timeline of technological evolution. If the same effect, such as a rise in diffusion or convergence I-values, can be observed for different products in the same time period, they might have some connection, such as events like a major war, or a major discovery. The possibilities are endless as long as the product characteristics are well chosen and organized, and enough data points are gathered. This is particularly important as was seen in out fighter study.

As a corporate instrument, it is particularly desirable. If carefully analyzed, its results can substantially improve the firm's decision making process. The classification method described in this paper allows a company to study how close it can get to its defined goal. With just the convergence results, that are more accurate for modern designs, one can cut some unknowns from the process. It is simpler to think of a decision tree with two branches splitting into smaller branches each. If a strategy is known, say a breakthrough is the desired outcome of a future design, than a firm must aim for a low convergence level. On the other hand if the company cannot afford any risk a high degree of converging technology is desired.

If the firm can estimate the information content on future competitors, and therefore calculate a preliminary diffusion value, a hard but doable task. Subsequently a complete classification can be obtained.

5. Biblography

[1] Frenken, K., Leydesdorff, L., *Scaling Trajectories in Civil Aviation (1913-1997), Research Policy* 29, pp. 331-348, 1999.

[2] Anderson, David A., *Caças Americanos da II Guerra Mundial*, Edições Siciliano, São Paulo, BR, 1984

[3] Cover, T. M., Thomas, J. A., *Elements of Information Theory*, New York: Wiley, 1991.

[4] Fermi, Enrico, *Thermodynamics*, Prentice Hall, 1937.

[5] Green, W., Swanborough, G., Mowinski, J., *Modern Commercial Aircraft*, Salamander Books, Ltd., London, 1987

[6] Gunston, Bill., *Caças Britânicos da II Guerra Mundial*, Edições Siciliano, São Paulo, BR, 1984

[7] Jackson, P., *Jane's All the World's Aircraft*, Jane's Information Group Coulsdon, Surrey, UK, 1995

[8] Jackson, Robert, *Modern Military Aircraft*, Chartwell Books, Inc., Edison NJ, 2003

[9] MacKay, David J.C., *Information Theory, Inference, and Learning Algorithms*, Cambridge University Press, 2003

[10] Mason, Francis K., *Caças Alemães da II Guerra Mundial*, Edições Siciliano, São Paulo, BR, 1984

[11] Nelson, R.R., Winter, S.G., *An Evolutionary Theory of Economic Change*, Belknap Press of Harvard University Press., Cambridge MA, 1982

[12] Saviotti, P., *Technological Evolution, Variety and Economy*, Edward Elgar Publishing, Cheltenham UK, May 1996

[13] Shannon, C. E., *A Mathematical Theory of Communication*, *Bell System Technical Journal,* 27, pp.379-423 & 623-656, July & October, 1948.

[14] Utterback, J.M., Abernathy, P., *A dynamic Model of Process and Product Innovations, Omega 3*, pp. 639-656, 1979

[15] Ries, Al & Laura, *The Origin of the Brands*, Harper Business, 2004.

[16] Schmookler, J., *Invention and Economic Growth*, Harvard University Press, Cambridge, MA, 1966.

[17] Dosi, G., *Technological Paradigms and Technological Trajectories*, Research Policy, 11,147-62, 1982.

[18] Movery, D. and Rosenberg, N., *The influence of Market Demand on Innovation: A Critical Review of Some Recent Studies,* Research Policy, 8, 103-53, 1979.

[19] Boeing Co. Website, **www.boeing.com**

[20] Empresa Brasileira de Aeronautica SA – Embraer - Website, **www.embraer.com**

[21] Airbus Industries Website, **www.airbus.com**

[22] Bombardier Aerospace Website, **www.bombardier.com**

[23] Federation of American Scientists Website, **www.fas.org**

[24] Global Security Organization Website, **www.globalsecurity.org**

[25] Wikipedia – The Free Encyclopedia, **www.wikiped**

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