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Cladistics applied to Aerospace

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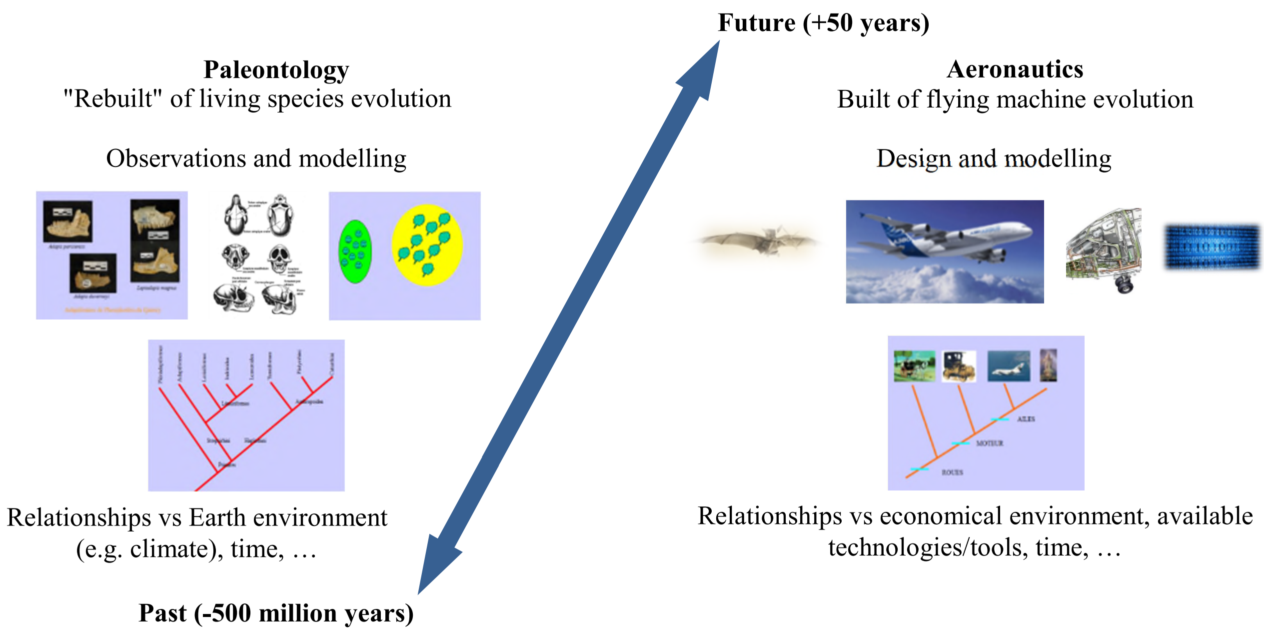
Abstract

To imagine a new Aircraft design and manufacturing, it is necessary to think in a new way and for instance to watch around us to identify some inspiration sources. Among them, one is to find inspiration from the living world in order to "think out-of-the-box" in terms of Aircraft technologies, architectures, etc. In this perspective, we applied the cladistics approach used for studying the biological evolution with the aim to highlight some innovative ways to revisit the current Aircraft configuration. This paper details an application of the cladistic analysis on aeronautics based on a set of Aircraft external characters.

1. Introduction

As a "normal/classical way of working", the main part of the Aircraft design is (and has been) done by aeronautics engineers who already studied a lot of Aircraft configurations and a non-negligible part of them was tested in the world for decades. The activities of design and manufacturing were performed with technologies available at that time such as materials (e.g. wood, iron, aluminium, composite), energy densities (e.g. mechanical, pneumatic, thermal, electrical), data processing performances (e.g. analogic, digital, centralized/decentralized, with/without pre-processing), … Additionally, these design and manufacturing activities occurred in a specific environment (e.g. with economic constraints, industrial work-sharing, competition landscape, crisis period) as existing at that time.
Then to imagine a new Aircraft design and manufacturing, it is necessary to think in a … new way and for instance to watch around us in order to identify some inspiration sources. Among the promising different ways to imagine some new Aircraft configurations, one is to find inspiration from the living world in order to "think out-of-the-box" in terms of Aircraft design solutions, architectures, … In this perspective, we applied an analysis methodology used for studying the biological evolution (i.e. the phylogenetic/cladistics approach) with the aim to highlight some new and innovative ways to revisit the current Aircraft configuration.
The below picture illustrates such parallelism between the evolution of living species and the aeronautics history:



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In biology, the cladistic analysis is a method of phylogenetic construction which means a construction of evolutionary trees. The key-purpose of these trees is to represent the relationships between species where such relationships result from the history of evolution that is measured in millions of years.

The expression "cladistic analysis", and more generally the so-called "cladistics", comes from the term "clade" (from the Greek *klados*, branch). This type of analysis identifies the successive branches all along the life history that are as many diversifications from ancestral species (see [6] for the history and topicality of cladistics).

2. The "cladistic analysis" method

The method is based on the concept of homology. In the field of biology, this concept appeared during the 19th century. Homology is a relationship of resemblance: it is considered as “homologous”, a feature that is present in various species and which is identified as "the same". This identity admits some potential changes in shape and function: for instance, the same bones which were first used for “manducation” (from Latin *manducatus*, past participle of *manducare* (“to chew”) i.e. linked to the digestive system) became in the evolution story, bones of the middle ear (i.e. auditory system). Then the reality of such identity is linked to ancestry i.e. what is said as homologous is linked to a common ancestry. In cladistics, the homology relation admits that a morphological feature occurs in two forms, an initial state and a derived state. The cladistic analysis identifies the common ancestries and the branches thanks to the derived states that are shared by different species (so-called "apomorphies" in cladistic domain). In biology, these morphological analyses are often accessible only to specialists, but sometimes it could be more … obvious. For example, all mammals (e.g. from the kangaroo to the blue whale or from the shrew to man) suckle their babies thanks to the lactary glands: the udders, which are not only an apomorphy of mammals (“Mammalia” as say zoologists) but also that are responsible for the name given to them (Latin: *mammula*).

Cladistic analysis is a basic approach to building evolutionary trees (see [1] for an exposition of the different current methods of building tree). Born from biology domain, it can however be applied to other fields and it has been realized early its conceptual proximity thanks to the study of manuscripts: typically, this method appeared to be applicable to conduct any investigation of historical kinship [4]. Therefore, the errors of copyists in the Middle-Ages can be assimilated to evolutionary innovations, to derived states suitable for linking the texts according to their degrees of common ancestry.

The first step in cladistic analysis is to identify the character states, formalized under a binary approach often by questioning: “is the character present or absent?” The second step is to estimate the direction of states transformation (so-called "polarity") where the most general criterion is the outgroup comparison. According to this criterion, during the study of any group of organisms, a state recognized in various organisms not belonging to the group studied is initial for the group studied; if on the contrary, it is present only within the studied group, it is derived (apomorphic) for the organisms which possess it. In other words, the outgroup comparison makes it possible to calibrate the degree of states generality. This approach is universal and applies to both morphological (i.e. shapes) and molecular (e.g. nucleotides) features. Intuitively, we understand that a feature shared by an amoeba and a giraffe is more general and older than a feature recognized only in ruminant mammals.

In terms of tools, the cladistic analysis is carried out by so-called “parsimony algorithms” which maximize the homology at its level of shared apomorphy (synapomorphy) through a measurement that is called the “Manhattan distance”. A computation is done to provide the distance between two points (e.g. between two species or two objects) according to a third point on which they are connected (e.g. the common stem, the branch, the ancestor). This point is the location of apomorphies. Based on this branches tree, the "kinship pattern" is the shortest tree. In terms of algorithm, the computation of the shortest tree is an NP-complete problem (i.e. a Nondeterministic Polynomial time problem) which gives a heuristic result but not optimal one when too many species or objects (i.e. beyond 20).

3. Aeronautics

The design and manufacturing of Aircraft has a long story from Clément Ader and the Wright brothers times to today period. The application of the cladistic analysis to the characteristics of Aircraft designed to fly by using technological innovations is the same as applying it to ancient texts: such technological innovation is applied to a type of Airplane and then to another one by combining/mixing other innovations, etc.

The challenges and objectives are multiple. Indeed, the analysis is a retrospective method: it reconstructs the ancestral states, the combinations of ancestor characters (i.e. technical features) from the characters of the descendants. In this

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perspective, an Aircraft is assimilated to a species or an organism. Its attributes are observed characters. The analysis focuses in priority firstly on the external characters i.e. the ones that are visible to the naked eye, such as a zoologist who studies the animal characters or a palaeontologist with his fossils.

Does it make sense to apply this method to reconstruct a history of aviation (or at least some of its technological innovations)? Cladistic analysis ignores chronological data and relies only on morphologies: but one can notice that the constructed tree provides combinations of characters at the nodes which are the ancestor characters. On the contrary, the dates of the first flights of the Aircraft are well known (but not necessarily the exact date of the driver-ideas). For instance, if two planes are found to be closely related because they have an exclusive common ancestor (they are said to be two “sister groups” i.e. “schwestergruppe” in German), does the ancestor characters combination make sense in terms of ancestral Aircraft? Does this combination say something about a common invention and does it make functional sense?

If it is the case then it is also possible to go beyond the biological transfer. The technological evolution of airplanes is partly due to “natural” selection, which is responsible for the fixing in species of "advantageous features" (to use the Darwin's expression): an airplane must be adapted to flight and any innovation must be - by principle - backed up by the idea of “advantage”. Nevertheless, the evolution here is “cultural”: Innovations are not just refinements of the previous steps; they can also come from other planes with more distant relatives. The multiple appearances in the tree of these innovations are in some way comparable to the “homoplasies” of biologists, that is to say evolutionary events which are not directly linked to the common ancestry but which have appeared independently. However, in the case of the aviation industry, the independence can come from imitation or even more from industrial espionage. Nature is complex and technological nature can be even more complex.

4. The "cladistic analysis" as applied on aeronautics

The analysis presented here is based on [2] and [3]. The analysis covers 68 aircraft from the Ader III aircraft and the Wright brothers aircraft of the late 19th and early 20th centuries (chosen as outgroups) to the Airbus A350 XWB as designed on 2013 (see table 1). These planes are thus assimilated to biological species. The morphological characters are 105 in number and address only to the external anatomy such as wing, engine, fuselage, cockpit, landing gear, tail, etc. They are gathered in a matrix of characters. The observations are coded there (see table 2) in the form of binary characters (example: wings = concave (0), plane (1)) or, for 45 of them, multi-state characters (example: retraction system landing gear = rearward (0), forward (1), inward (2), outward (3)).

Aircraft	1st flight	Manufacturer / country
Ader III	1897	- /
Wright Flyer	1903	- /
Santos-Dumont 14 bis	1906	- /
Blériot XI	1908	- /
Antoinette VII	1909	Antoinette /
Avion Henri Coanda	1910	- /
Vlaicu III	1914	- /
Fokker Dr.I	1917	Fokker /
Farman F60 Goliath	1919	Farman Aviation Works /
Armstrong Whitworth AW 155 Argosy	1926	Armstrong Whitworth Aircraft /
Spirit of Saint Louis	1927	Ryan Airline Compagny /
Fokker FX	1927	Fokker /
Handley Page 42	1930	Handley Page /

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Aircraft	1st flight	Manufacturer / country
Junkers JU52	1932	Junkers /
Northrop Delta	1933	Northrop Corporation /
Boeing 247	1933	Boeing /
Lockheed Electra	1934	Lockheed Aircraft Corporation /
Douglas DC3	1935	Douglas Aircraft Corporation /
Boeing 307 Stratoliner	1938	Boeing /
SNCASE SE161 Languedoc	1939	SNCASE Sud-Est /
Beechcraft S35 Bonanza	1945	Beech Aircraft Corporation /
Boeing 377 Stratocruiser	1947	Boeing /
Northrop YB-49	1947	Northrop Corporation /
Vickers Viscount	1948	Vickers Armstrong /
Breguet Deux-Ponts	1949	Breguet /
Nord 2501 Noratlas	1949	Nord Aviation /
Lockheed L1049 Super Constellation	1951	Lockheed Aircraft Corporation /
Comet	1952	De Havilland /
Boeing 707	1957	Boeing /
Tupolev 114	1957	Tupolev /
Lockheed L329 JetStar	1957	Lockheed Aircraft Corporation /
Sud Aviation SE210 Caravelle	1959	Sud-Aviation (SNCASE) /
Armstrong Whitworth AW 660 Argosy	1961	Armstrong Whitworth Aircraft /
Boeing 737	1967	Boeing /
Tupolev 144	1968	Tupolev /
Boeing 747	1969	Boeing /
Concorde	1969	Aérospatiale /
XB-70 Valkyrie	1970	North American Aviation /
Douglas DC10	1970	Douglas Aircraft Corporation /
Lockheed L1011 Tristar	1970	Lockheed Aircraft Corporation /
VFW-Fokker 614	1971	VFW-Fokker /
A300	1972	Airbus /
BA Jetstream 31	1980	British Aerospace /
BA 146/Avro RJ	1981	British Aerospace /
A310	1982	Airbus /
Antonov 124	1982	Antonov State Compagny /

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Aircraft	1st flight	Manufacturer / country
ATR 42	1984	ATR /
Fokker 100	1986	Fokker /
A320	1987	Airbus /
Antonov 225	1988	Antonov State Compagny /
ATR 72	1988	ATR /
Dornier 328	1991	Dornier Flugzeugwerke /
Bombardier CRJ 100	1991	Bombardier Aerospace /
A340	1991	Airbus /
A330	1992	Airbus /
Boeing 777	1994	Boeing /
Embraer ERJ 145	1995	Embraer /
Embraer 195	2004	Embraer /
A380	2005	Airbus /
Falcon 7X	2005	Dassault Aviation /
Solar Impulse HB-SIA	2009	- /
Boeing 787 Dreamliner	2009	Boeing /
A350-XWB	2013	Airbus /

Table 1: Sampling list (i.e. 63 Aircraft)

N°	Criteria
1	Wings shape (Concave , Plane)
2	Number of wing-planes (Monoplane , Biplane , Triplane)
3	Landing gear, LG (Absent , Present)
4	LG types (Classic , Tricycle , Quadricycle , Single-track)
5	LG degree of freedom (Fixed , Retractable)
6	LG retraction (Not fully , Completely)
7	LG retraction system direction (Backward , Forward , Inward , Outward)
8	Main LG wheels composition (Single , Diabolo , Bogie)
9	Additional LG between the 2 main LG (Absent , Present)
10	Track in relation to the fuselage diameter (Upper , Lower , Equal)
11	Type of secondary LG (Pad , Wheel)
12	Secondary LG wheel composition (Single , Diabolo)
13	Connection between the main LG (No , Yes)
14	Number of LG legs visible for the main LG (1 , 2 , 3 , 4 and +)
15	Fork at the level of the main LG strut (Absent , Present)
16	Main LG (support) strut (Absent , Present)
17	Main LG wheel type (Spoked wheel , Solid wheel , Thick tire and rim)

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N°	Criteria
18	Main LG location mounting on (Fuselage , Wing , Engine nacelle)
19	Main LG wheels total number (1 , 2 , 4 , 8 and +)
20	Propeller (Absent , Present)
21	Propeller blades number (multiple of 2 , multiple of 3)
22	Propeller composition (Single , Double (= Contrarotative))
23	Propeller blades end shape (Sharp , Curved , Straight)
24	Struts (Absent , Present)
25	Canard configuration (No , Yes)
26	Fuselage (Absent , Present)
27	Fuselage deflection (Null , Upsweep , Downsweep)
28	Fuselage section shape (Quadrangular , Triangular , Hybrid , Ellipsoid)
29	Fuselage section proportion (As high as wide , Wider than high , Higher then wide)
30	Fuselage section ellipsoid (Regular , Flattened bottom , Flattened top)
31	Double deck (No , Yes)
32	Fuselage section symmetry along the width axis (Yes , No)
33	Cockpit (Absent , Present)
34	Cockpit shape (Open to the outside , Closed)
35	Canopy on fuselage (Absent , Present)
36	Canopy composition (One row of windows , Several rows of windows , Windows in front and above)
37	Nose shape (Straight , Curved , Sharp)
38	Nose length (Short , Long)
39	Windows (Absent , Present)
40	Window shape (Quadrangular , Hybrid , Ellipsoid , Triangular)
41	The angles formed by the windows (Straight , Curved)
42	Window proportion (As high as wide , Wider than high , Higher then wide)
43	Windows rows number along the fuselage (1 , 2)
44	Wing dihedral (Null , Positive , Negative , Mixed)
45	Wing dihedral as wing part (The whole , A part)
46	Wing position on the fuselage in frontal view (Median , High , Parasol , Low)
47	Wing type (Sweep , Delta)
48	Swept wing shape (Rectangular , Elliptical , Trapezoidal)
49	Swept wing shape (Right wing , Swept wing , Inverted swept wing)
50	End-wing structure (None , Winglet , Wing tipfence , Sharklet)
51	Belly fairing (Absent , Present)
52	Flap outlet rail fairings (Absent , Present)
53	Wing-root location on the fuselage (Anterior part , Posterior part , Middle)
54	Horizontal rear tail (Absent , Present)
55	Vertical rear tail (Absent , Present)
56	Rear tail type (Cruciform , V-shape)
57	Rear stabilizer position on the rudder (Low , Middle , High)
58	Horizontal rear tail plan dihedral (Null , Positive , Negative)

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N°	Criteria
59	Fin number (1 , 2 , 3 , 4)
60	Fin shape (Quadrangular , Hybrid , Elliptical or Curved , Trapezoidal)
61	Horizontal rear tail shape (Quadrangular , Elliptical or Curved , Triangular , Trapezoidal)
62	Horizontal tail edges parallel (No , Yes)
63	Horizontal rear tail proportion (As long as wide , Longer than wide , Wider than long)
64	Fin end (Fixed , Movable)
65	Fin mobile part type (Straight , Overfitted)
66	Vertical rear stabilizer dorsal extension on the fuselage (Absent , Present)
67	Twin-boom structure (No , Yes)
68	Elongation (Low , Moderate , High , Very high)
69	Main door (MD) on the fuselage or cockpit (Absent , Present)
70	MD number on one side (1 , 2 , Between 3 and 5 , 8)
71	Symmetry of the number of MD between the fuselage right side & left side (No , Yes)
72	Antenna (Absent , Present)
73	APU (Absent , Present)
74	Fuselage curve number in lateral view (1 , 2)
75	Photovoltaic cells (Absent , Present)
76	Fuselage-end location vs rear tail (Before , At the same level , After)
77	Engine attached to the wing (No , Yes)
78	Engines number attached to the wing (2 , 4 , 6 and +)
79	Engines location attached to the wing in front view (Above , Below , In wing axis , In wing axis and below)
80	Engines location attached to the wing in side view (Leading edge , Trailing edge , In the wing length)
81	Engine attached to the fuselage (No , Yes)
82	Engines number attached to the fuselage (1 , 2 , 3 , 4)
83	Location of the engines mounted on the fuselage in side view (Rear , Front , Front and rear)
84	Location of the engines mounted on the fuselage in front view (In the axis , Beside , Above , Above and beside)
85	Engine air inlet (Absent , Present)
86	Air inlet type (Small and complementary to the propeller , Main)
87	Main air inlet shape (Curved , Oval , Quadrangular)
88	Lights (Absent , Present)
89	Lights position on the wings (In the wing middle , At the wing end)
90	Mitre (Absent , Present)
91	Karman (Absent , Present)
92	Aileron (Absent , Present)
93	Flap (Absent , Present)
94	End-wing tip dihedron (Fixed , Variable)
95	Nose (Fixed , Variable)
96	Structure material (Fabric , Wood , Wood and fabric , Metal)
97	Canopy coating material (Fabric , Wood and fabric , Metal)
98	Engine nacelle separated from the fuselage (Absent , Present)

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N°	Criteria
99	Engine nacelle end (Closed , Open)
100	Open engine nacelle end edge (Smooth , Carved)
101	Visibility of the engine end cone behind the open engine nacelle (No , Yes)
102	Additional emergency exit (Absent , Present)
103	Fuselage end (Straight , Curved , Convergent)
104	Tail type of tail (Type 1 , Type 2 , Type 3)
105	Visibility of the fuel tank under the wing (Absent , Present)

Table 2: List of the 105 morphological characters used for the phylogenetic analysis

The software chosen is PAUP, version 3.1 [5] which has the advantage over its more recent versions of providing an unsurpassed character optimization algorithm at nodes. The parsimony analysis (TBR heuristic search algorithm) provides 64 trees with a minimum length of 639 steps (or 639 transformations in total). From the 64 trees is calculated a strict consensus tree which retains all the nodes common to all the trees (see Figure 1 where the length of the branches is proportional to the number of transformations, that is a "phylogram"). The so-called retention index which expresses the quality of the structuring of the tree is average (0.63 - knowing that an optimal structuring has an index of 1). It appears that the contradictions between the 64 trees affect practically only two zones of Figure 1, the first dichotomy (node 113) and that initiated by node 85 (including nodes 83, 81). One can deduce a good structuring of the data despite the importance of homoplasies revealed by the retention index. An option for solving the multifurcation corresponding to node 85 is provided by a majority consensus tree (which abandons the topographies less often represented (see Figure 2). Node 81 of Figure 1 is thus solved between two sister groups composed of by the Douglas DC10 and the Airbus A380 on the one hand, and on the other hand, by the Airbus A350 and the Boeing 787.

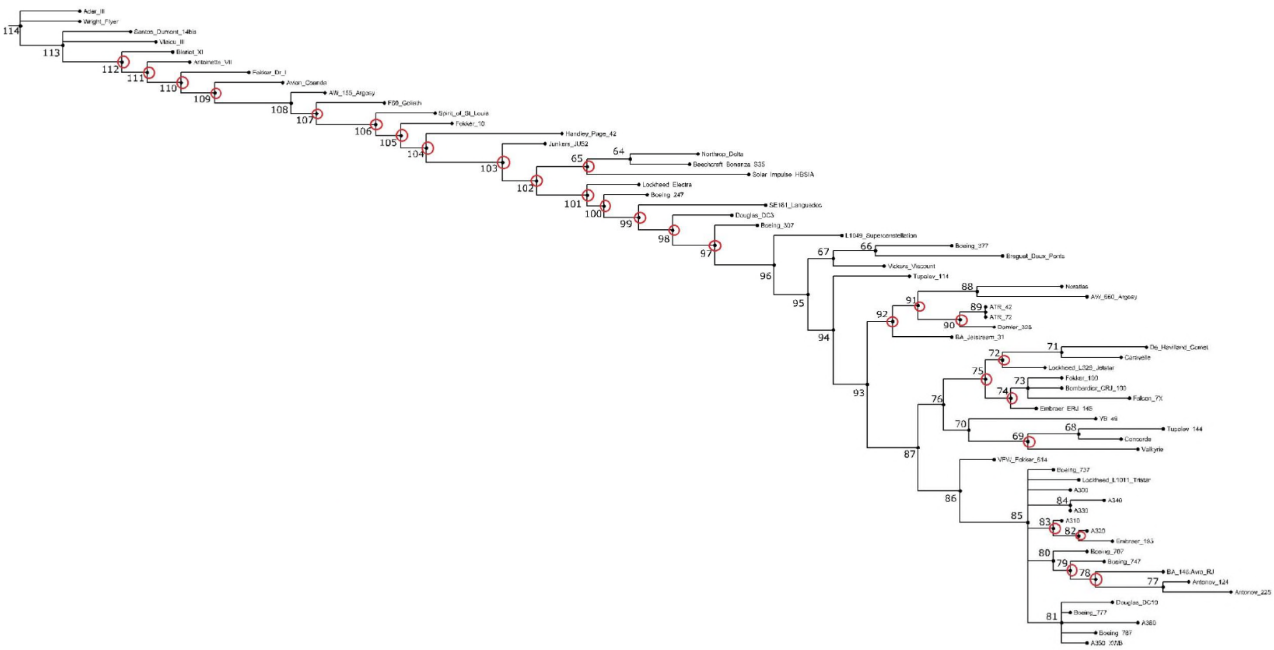

Figure 1: Phylogram based 64 parsimonious trees obtained from a heuristic analysis

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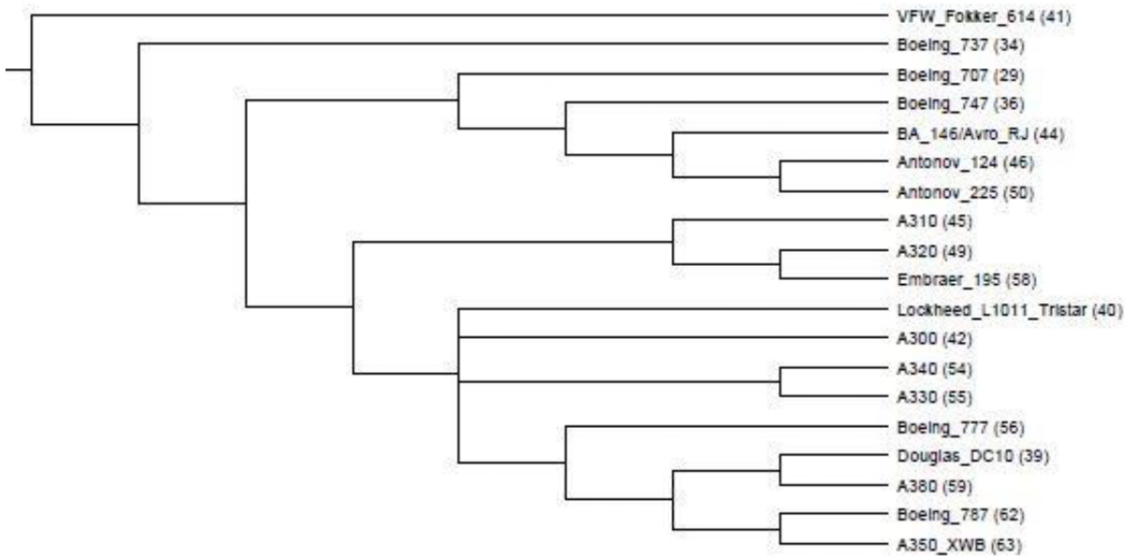

Figure 2: "zoom" on the node 86 of the majority consensus (at 50%) tree at location of a polytomy

The first multifurcation (node 113 in Figure 1) illustrates the technological hesitations with three trials or with three evolutionary paths: the path of the Santos-Dumont (plane "mounted upside down"), the path of the Vlaicu III (engines located at the front-part and rear-part) and the path of node 112 from which all the other planes derive, expressing adaptive success, a "radiation" according to the naturalist term.

4. Conclusion

As illustrated by this insight, a cross-fertilization between the specialists on "life evolution" analysis (i.e. "cladistic analysis") and the aerospace designers is fruitful to provide some sources of inspiration in order to imagine the next generation of Aircraft. Indeed, it allows to highlight the main "branches of the tree" describing the Aircraft evolution since the beginning aviation up to now: then by focusing on some specific "branches", it is possible to re-think and to re-assess if the Aircraft configurations aborted at that time are still a non-beneficial configurations with today progresses on technologies such as new materials, higher energy densities, faster data processing performances.

The proof-of-concept in hands shows that the history of aviation is generally well restored by the cladistic analysis of the 105 external characters. It can be concluded that aeronautical engineers have followed an evolutionary logic close to adaptation to the environment. The highlighted relationships largely represent the state of technological knowledge at a given period. One can imagine that future adaptive constraints will continue to impact the airplane shapes in terms of energy saving, greener airplanes, improved performances (e.g. with increase the range), etc.

More generally, all the potential connections between the biology and aerospace domains (vs cladistic methods, biomimicry …) have to be developed with the aim of generating news ideas to optimise the Aircraft design solutions, architectures, operations, …

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