ASTRID - AIRCRAFT ON BOARD SYSTEMS SIZING AND TRADE-OFF ANALYSIS IN INITIAL DESIGN

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Abstract. Unlike the past, when the system view of the airplane was not at all evident and the results of the conceptual design were almost exclusively turned into the preliminary definition of the airplane main characteristics, today the systems engineering approach is widely accepted and appreciated and the results of the conceptual design include also initial basic choices for onboard systems. We can say that, as the proposed new approach guarantees more accurate and detailed definition of an aircraft concept and makes more effective the development process, ASTRID represents a real improvement of the tools available for Aircraft Conceptual Design.

Keywords. On board Systems, Conceptual Design, Systems Design.

1 Introduction

It is well known how in modern aircraft the relevance of Systems (Avionics and “Not Avionics”) is continuously increasing [1]. This fact is summarized in Figure 1, by considering the aspects of cost, weight, and Maintenance Actions frequency and considering as Systems the Avionics and the Aero-electro-mechanical Systems (or “Non Avionics Systems”), both compared with Structures and Engines.

It is also accepted that the Conceptual Design phase has strong relevance in defining technical and economics characteristics of a future aircraft, as great part of more relevant choices, during the development, are made in conceptual design phase, as shown in Figure 2.

Even the already two mentioned aspects seems to be clear, nevertheless it has to be considered that Avionics and On Board Systems, at least for the wide differences among the various systems, are not easy to be assessed with few and simple relationships like aircraft sizing in Conceptual design phase [2]; moreover, it has to be noticed that consolidated approaches and habits lead to see the start of development of Avionics and On-Board Systems only after that at least a preliminary “concept of aircraft" has been defined. This sequential approach – Aircraft Conceptual Design - Avionics and On Board Systems preliminary assessment – is yet the current State of the Art.

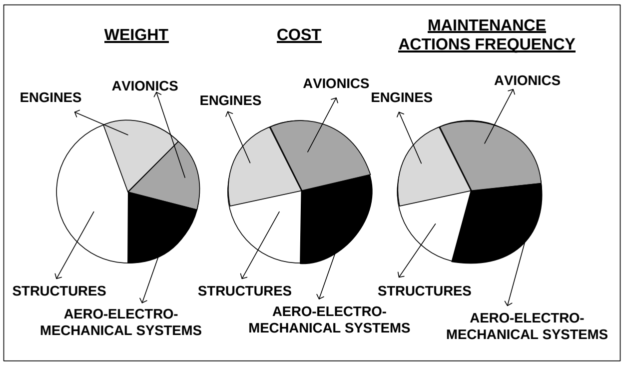

Figure 1 Relevance of On Board Systems

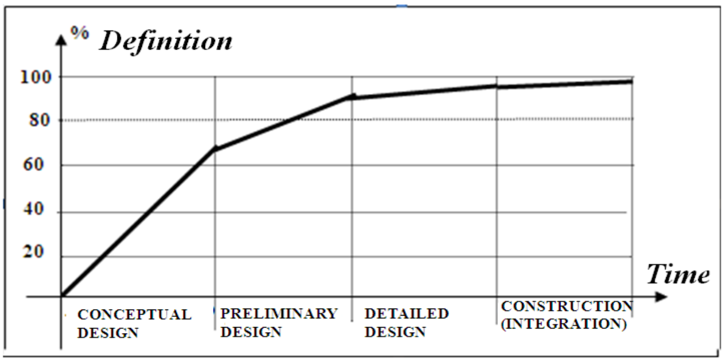

Fig. 2 Conceptual Design relevance [1]

As a confirmation of this, some specific books can be mentioned, among the more appreciated currently available, such as Daniel P. Raymer's Aircraft Design: a conceptual approach[3] and Jan Roskam's Airplane Design- Volumes I to VII[4]. In the table of contents of Raymer's book the first 9 of 24 chapters are entirely dedicated to issues such as "Sizing from a conceptual sketch", "Airfoil and geometry selection", "Thrust-to-weight ratio and wing loading" and "Special Considerations in Configuration Layout"; only chapter 10 is dedicated to "Propulsion and fuel system" and chapter 11 is dedicated to "Landing Gear and Subsystems" and it is easy to notice that the focus is put on systems that have the largest impact on the architecture of airplane. In the titles of remaining chapters there is no other mention to Avionics and On Board Systems, even with chapter titles referring to "Weights", "Stability, Control, And Handling Qualities" and "Cost Analysis".

As far as concerns the extremely detailed Jan Roskam's "Airplane Design", ahead the topics of the 8 parts, even in this case it can be seen as the architecture of Systems (particularly for Landing gear, as already said, extremely integrated in the configuration of aircraft) appears clearly only in the middle of the design process, for its earliest 3 parts focused on the aircraft.

It is worth remembering that, from Raymer's and Roskam's works, software tools derived and became widespread, also at industrial level; these tools are RDS – "Integrated aircraft design and analysis", by Conceptual Research Corporation (Company founded and lead by Daniel Raymer) and

AAA – “Advanced Aircraft Analysis”, by DAR Corporation (founded by Jan Roskam); these software tools by one side underline the great value and the relevance of Raymer’s and Roskam’s work, by the other they confirm that, according to the detailed description of the two software available on web, the two methodologies carry on the preliminary design of aircraft, without, clearly developing in an organic way Avionics and on board general Systems. It is clear that today nobody rejects the relevance of Avionics and on board general Systems, but, simply a tool to evaluate them since earliest phases of design development of a new aircraft is not available; about this point, it is worth mentioning another great expert of “Conceptual Design”, prof. J. Fielding from Cranfield University; in his book [5] “Introduction to Aircraft Design”, right after the introduction, he points out the following questions: “Why should we design a new aircraft ?”(chap. 2), “What is it the shape?”(Chap. 3 and 4 for Civil aircraft and “others”) and “What’s under the skin?”, discussing about structures (briefly) and Avionics and on board general Systems, which take almost 40 pages of the overall 180; only after that, the classical methodologies of Conceptual design are discussed and some example of design developed among Cranfield College of Aeronautics are described. Fielding’s work confirms therefore the relevance of Avionics and on board general Systems and the needs of considering them since the initial phase of design process; obviously, being this book focused on the description of the problem of aircraft design and not on its solution, also in this case no methodology is provided.

From this assessment, even if synthetic, of the State of the Art, it seems that it is accepted that Systems are considered in early phase of a new airplane design only from the point of view of their weight, that is a part of Empty Weight of the plane. In several papers about Weight Estimation, that is a typical tool for Conceptual Design, the Systems weight is carefully considered [6], [7], but the Weight Estimation Relationships (WERs) concerning the Systems present some relevant lacks:

- The weight, in more simple methodologies, is estimated for all Systems together, not for every particular System
- In more detailed methodologies [8], [9] the weight is estimated for every system but not at level of main equipments that constitute the system; simply, the configurations of the various systems are not still considered
- If the weight of various systems is derived, the same doesn’t happen for relevant technical characteristics like power requested and volumes. That implies that, at conceptual design, the so called 2-ary Power [10] is not considered; please note that 2-ary Power is some percentage of the whole power utilized by the plane, but this is no more negligible considering the energetic cost growing as well the ecological issues. In the same time the lack of estimation of systems volumes doesn’t allow a correct definition of plane volumes and the lack of information of main equipments weight and location doesn’t allow to reliable evaluation of CoG location and of moments of inertia.

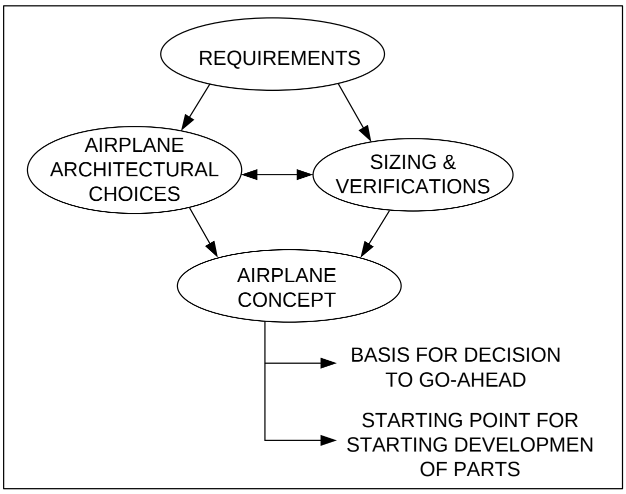

Figure 3 Airplane Conceptual Design

Figure 3 shows as a typical Conceptual Design Process is usually driven up [2], and the aforesaid lacks negative effects seem clear. By comparison, the addition of a new module devoted to Systems, at conceptual level, as shown in Figure 4 could mean a great improvement to Conceptual Design methodology, with the advantages pointed out in such a figure.

From the assessment, even if synthetic, of the State of the Art, it seems there is no tool available that can be assimilated or at least compared to the one hypothesized in Figure 4. If this tool will be developed in a satisfactory way, apart from providing a relevant support in the industry process of development of new aircraft, a very good result in terms of innovation would be achieved; how to reach this goal, is the topic of the next parts of this paper.

2 Systems Conceptual Design

In order to obtain a Systems Conceptual Design tool, to obtain the advantages above discussed, the Authors have developed ASTRID - (Aircraft on board Systems Sizing And Trade-Off Analysis in Initial Design phase) that is a methodology and the SW module to implement it.

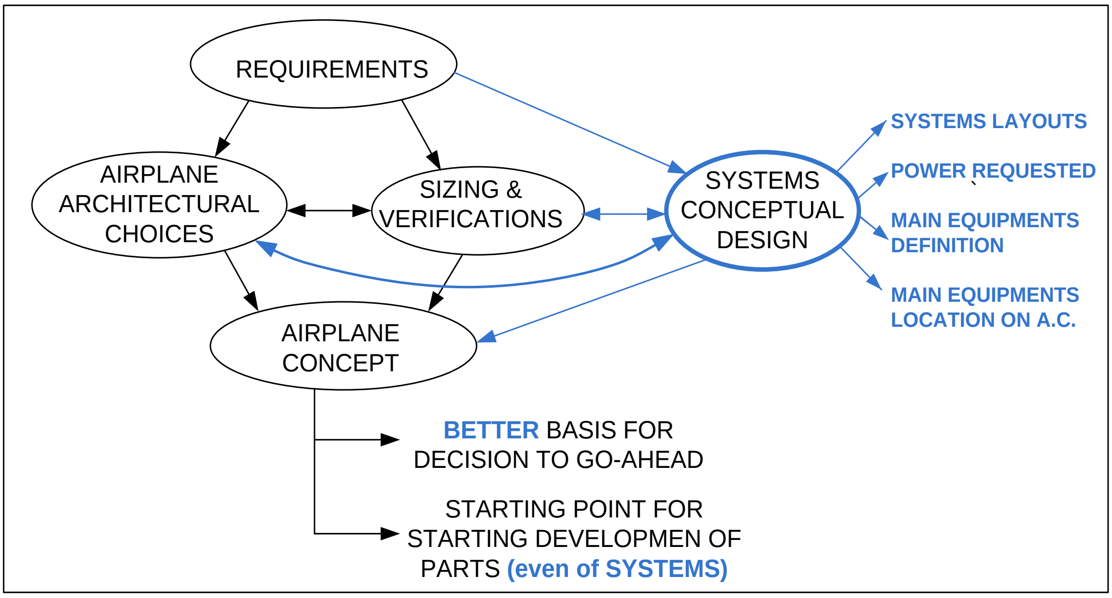

Figure 4 Airplane and Systems Conceptual Design

ASTRID has been planned to obtain a first definition of Avionics and On Board Systems for a plane defined at Conceptual Level; it must be capable of easily performing iterations and successive refinements and to make the evaluation and comparison of various Systems Configuration possible alternatives.

Before getting into the details of the logical steps that have to be taken to apply ASTRID methodology, a synthetic overview of the complete methodology is given by Figure 5.

At first it is illustrated how ASTRID could be utilized to define the whole Systems configuration for a Concept of plane elaborated by a Conceptual Design Methodology; the interchange file will be utilized, if necessary, if ASTRID will suggest any changes in concept of plane, to a further iteration by Conceptual Design Methodology. By the way, if the above described is the classical way of operating, ASTRID could operate in other ways; from Figure 5 it can be observed:

a) ASTRID could be operate non on a Concept plane elaborated by Conceptual Design Methodology, but, for example, on any plane of which the Operator would assess one or more

Systems; clearly, in this case, the Operator will introduce all requested data of the plane, and, of course, no iteration on Plane characteristic will be possible

b) The Operator will operate on a “Design”, where Design means a solution for all or part of the Systems of a Plane. ASTRID allows to have more Designs (i.e. more alternative of Systems Configuration) for the same plane, that is particularly useful to perform trade-off or comparisons.
c) To avoid confusion every Design must be initialized with an identification name and with association to the Code of the Plane; if the Plane is a Concept derived by Conceptual Design Methodology connected, the Code is automatically generated.
d) A Design after initialization can be under work or not, at the moment, utilized: in such a case it is stored in Data Base of Open Designs and, at every time, it can be recalled to be modified or to have further advance. When a Design is considered completed and satisfactory, it can be officialised and it will be stored in Data Base of Official Designs; it will no more able to be modified.

Than the Figure 5 illustrates how ASTRID can be studied, obviously in a preliminary way, the main Systems of a plane; as it will later discussed the various System will be treated in different way following their peculiarities, by the way some common strategies will be utilized. In particular the new tool shall not therefore be aimed at level of the single systems (for example as ATA subdivision) but, for each system, at level of its main equipments (i.e., for instance, in the avionic system: weather radar, AHRS, ADC, VOR, radio UHF, etc.; in the electrical system: generators, TRUs, inverters, batteries, etc.). Thanks to this approach four main advantages that may lead to a better definition of the whole aircraft very early during the design process can be envisaged: possibility of defining the various systems architectures, even if simplified, very early during the design process;

a) possibility of achieving a reasonable confidence of the capability of the systems to perform their assigned functions (by sizing or by the choice of the main equipment);
b) capability of carrying out installation study, in particular of defined main equipments, of which functionalities, volumes ad weight are known; this installation study become available very early during the design process, thus being able to estimate the influences on the centre of gravity position and inertia moments.
c) capability of preliminarily estimating safety and reliability and performing an initial assessment of maintainability/accessibility with optimization of the turn-around operations [11], [12], [13].
d) Last but not least an early, even preliminary, definition of main equipments allows to anticipate preliminary contacts with potential Suppliers.

After the aforesaid general consideration about ASTRID, always by referring to Figure 5, it is clear that the core of the methodology is constituted by the blocks dedicated to the various Systems. It is to noticed that such blocks are independent but the operator can continuously consult how already defined, obviously for the same Design, for the other Systems. In plus data of a System, certainly needed for defining another (example, electric Power requested by Avionic is absolutely necessary to define Electric generation), will be automatically passed (of course, only if already calculated) to the module that need them, when the Operator will utilize it.

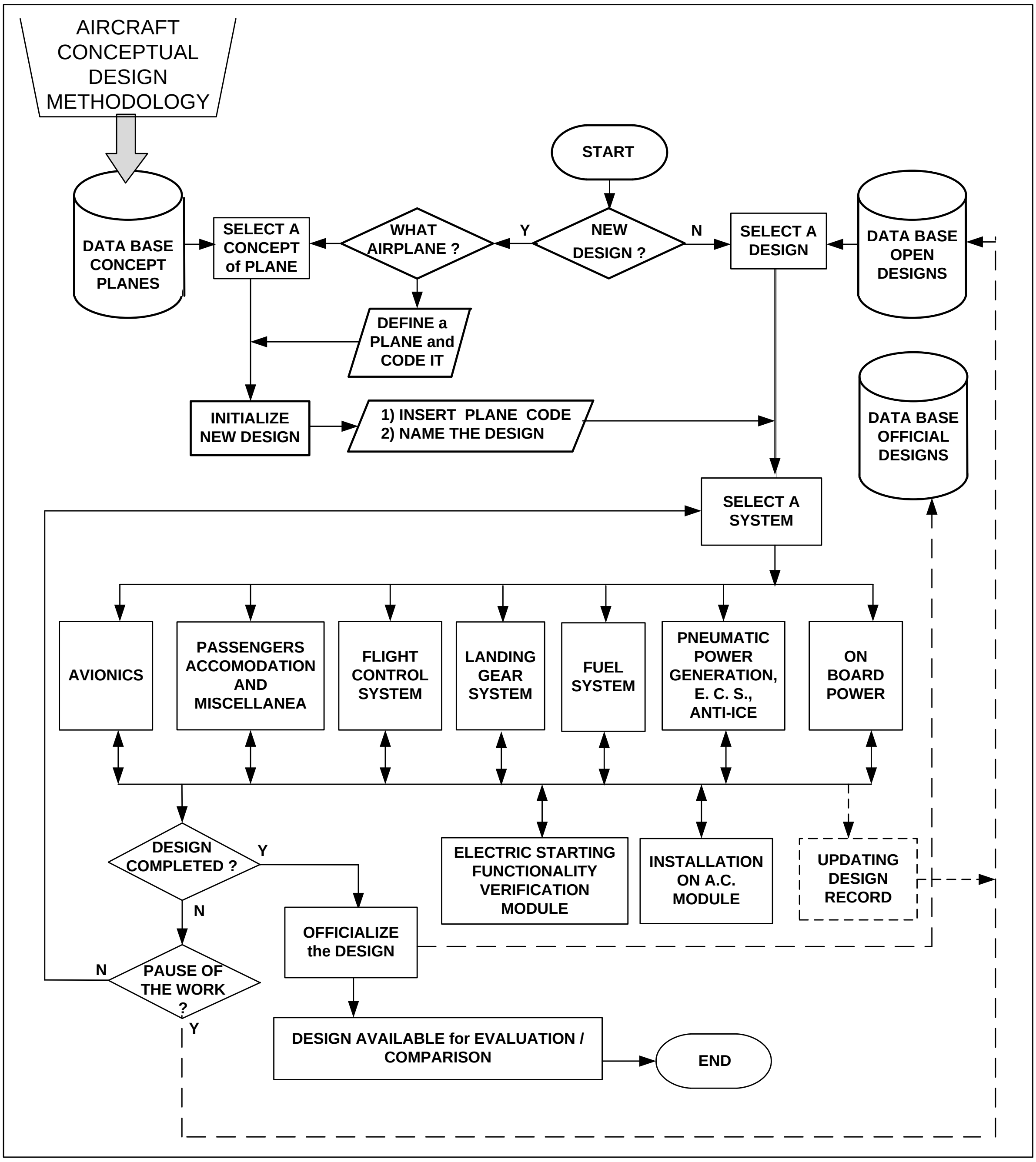

Figure 5. ASTRID Methodology organisation

Now the various modules will be shortly illustrated:

2.1 Avionics definition at conceptual level

Figure 6 summarize how ASTRID can support the Operator in defining the Avionic System, at Conceptual Level; the first options offered to Operator are to define a functional Tree of the System and to define (or receive if already defined, for example during the Plane Concept definition), the Mission Profile. On the basis of the functions to be performed, the Operator will choose the Avionic Equipment, i.e. in this case, the Main Equipments; during the choice the Operator can be supported by

ASTRID that, if requested, is able to suggest a typical and exhaustive list of kind of Avionic Equipment parted into typical Avionic Sub-Systems. On the basis of the defined list of Equipments the operator will access to Data Base (offered by methodology) as well to external sources, for example the Web, in order to search the better solution, for every Equipment, available “off the shelf”. In case that an available solution is not found, or not accepted, ASTRID can offer statistical estimation of weight, volumes [14], power requested, as function of specified performance parameter and/or kind and level of technology. In this way the all main equipment will be defined, so ASTRID will able to draw the block scheme of the Avionic System. Another feature, particularly useful, is the capability of summing the Equipments Weight and the Power requested (electric, of well specified kind, and cooling request) in the various phases of the Mission Profile.

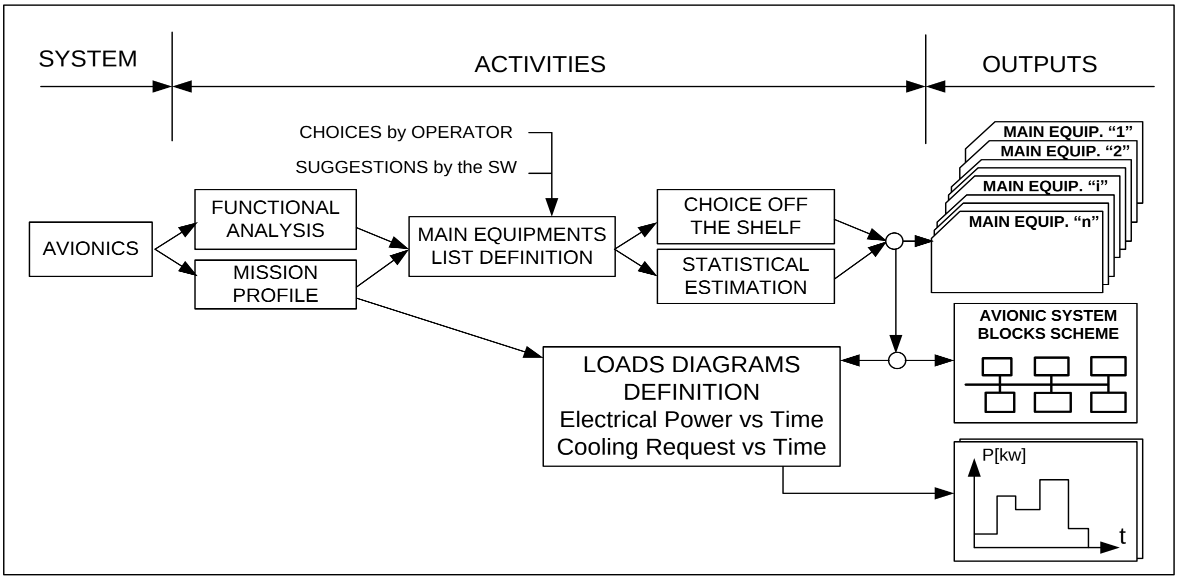

Figure 6 Avionics definition at conceptual level

2.2 Passengers accommodation and miscellanea

Furnishing, Cabin lights, Audio System, IFEC, Galleys and Toilets (see Figure 6) are a list (perhaps not exhaustive) of Systems devoted to Passengers accommodation; all these Systems, grouped, can represents a remarkable part of Empty weight and a remarkable portion of Power spent on board. So a correct definition of these part of Systems configuration can be of great advantage in Conceptual Design phase of a new passengers plane. ASTRID can support the Operator in definition of such a part of Systems configuration with a module that works in the same way of the previous considered Avionic Module. As Figure 7 shows, the Module will allow:

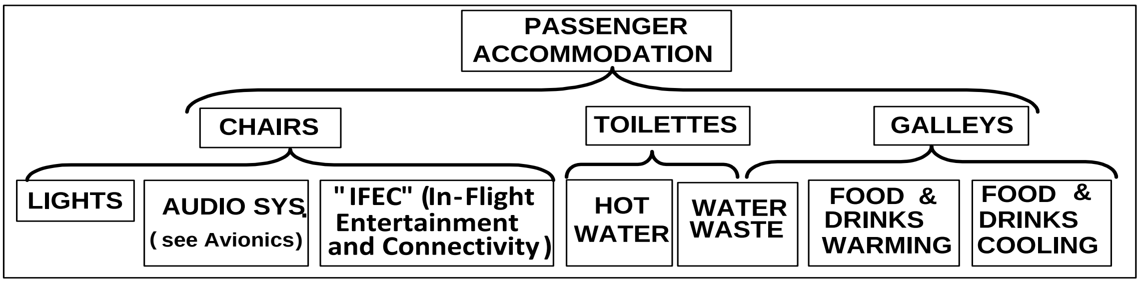

Figure 7 Passengers Accommodation related Systems

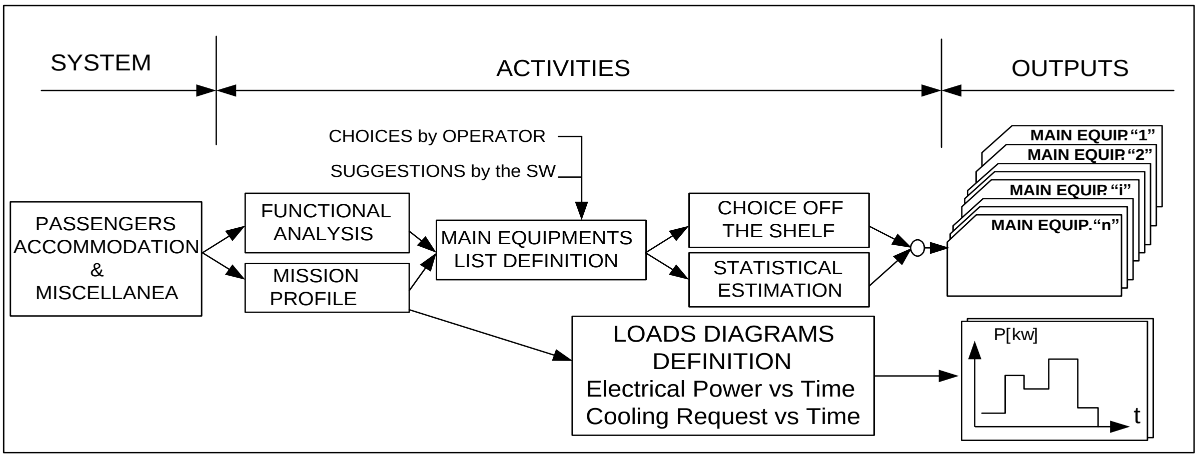

Figure 8 Passengers Accommodation related Systems definition at conceptual level

a) to define the Main Equipment List on the basis of Functional Analysis and of Mission Profile
b) to define every Main Equipments on the basis of a "choice off the shelf", or, in different case, with a statistical estimation of Weight, Volumes and, if applicable, Power requested.
c) Total weight of all Main Equipments and Power, with definition of kind (AC or DC, voltage, etc.) requested in various phases of Mission Profile will calculated too.

2.3 Flight Control System – FCS

The Flight Control System is certainly one of the Systems more relevant for a future Airplane, at the moment, in conceptual design phase. In this case it is particularly necessary to know:

a) How many mobile surfaces will be present on the new plane, how their will be, eventually, connected (for example aileron right and left) ?
b) How much will be the dimensions (mean chord, surface) of such surfaces, how much their angular excursions and relative no load angular speed requested ?
c) How surfaces will operate in normal way and in reversionary way ?
d) What will be, for every actuator the sizing conditions (dynamic pressure, attitude, angular excursion) ?
e) How actuators and of what kind will drive every surface ?

The answers to all aforesaid question, practically, will define the configuration of the Flight Control System (example in Figure 8); in the case that the answers has not been known from Airplane Conceptual Design, ASTRID, as Figure 9 shows, will request the relative questions to the Operator, and will provide to estimate (if not already available) related data as hinge moments; a simple estimation of such moment is illustrated in Figure 10.

Every actuator hypothesized (Fig. 8) will be now preliminary sized by ASTRID by the procedure shown in Figure 11; in such a figure it is illustrated the classical sizing of an hydraulic linear actuator by considering the so called "Stall Load" (the Force given by the actuator at speed =0) and the "No Load Speed", i.e. Force=0 (at maximum actuator speed); the parabolic curve defined by thesetwo points describes all the possible way of running of the actuator with related speeds, or (second diagram) the aforesaid Force by the arm of actuator (i.e. the moments produced by actuator) and related angular speeds of the surface around the hinge.

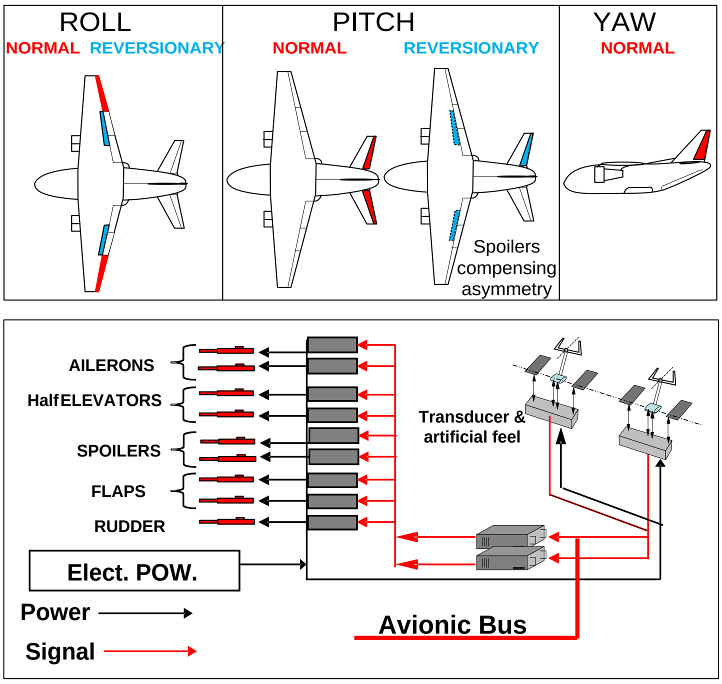

Figure 9 Flight Control System: example of configuration

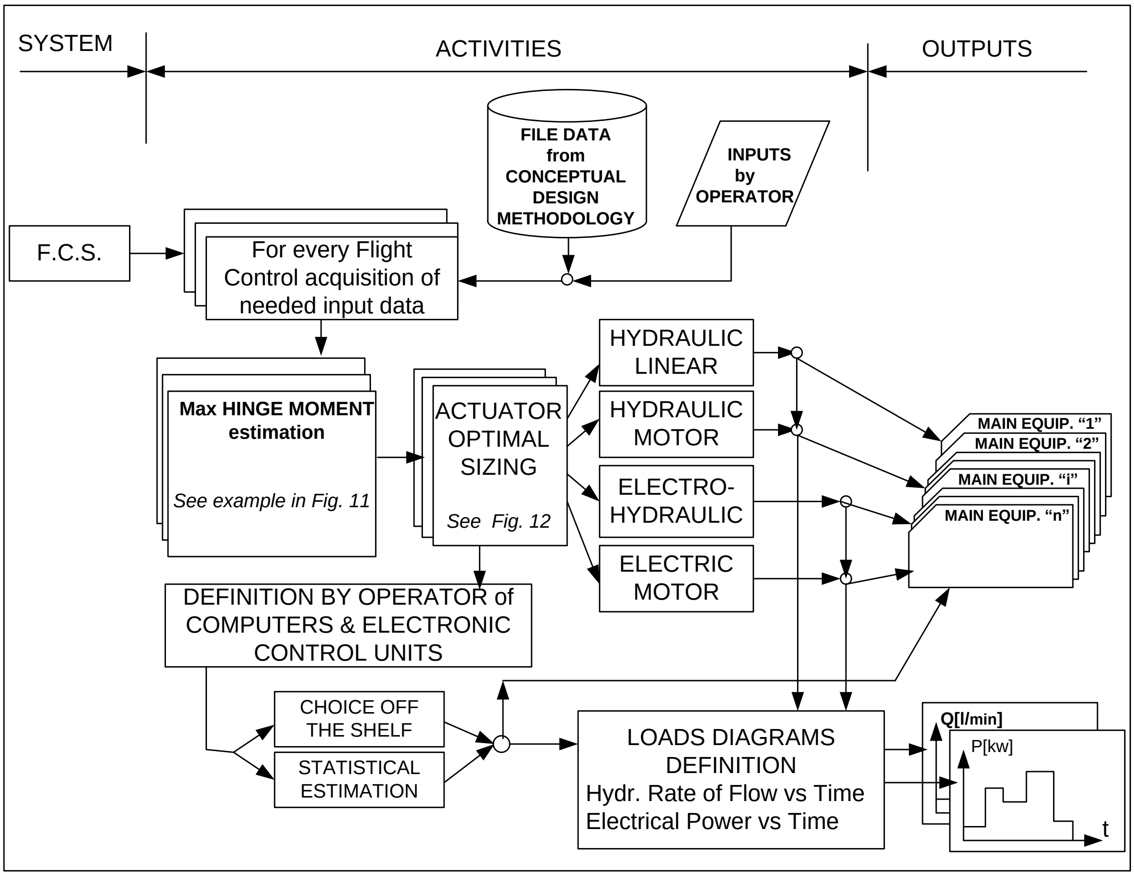

Figure 10 Flight Control System definition at conceptual level

The second diagram so can be applied both to linear and rotary actuator; please note that it is usual to obtain the same effect of a linear actuator with a rotary one with a screw jack; of course it is necessary hypothesize the relative reduction ratio. The case of hydraulic motor shows as it easy to consider an electric motor (with possibility of define its size) equivalent to the hydraulic one; in this way it will be possible to choose both hydraulic and electric actuators and then to size them. In addition it will be possible to define the optimal rate that is= No Load Speed divided per 1.73. Figure 12 shows this fact either in the case of hydraulic linear actuator (the aforesaid parabolic curve is in diagram Force-Linear Speed) and of hydraulic motor (diagram Torque-Angular Speed); both cases could be applied in case of hydraulic linear actuator, considering that force of linear actuator per its effort arm gives the moment [15].

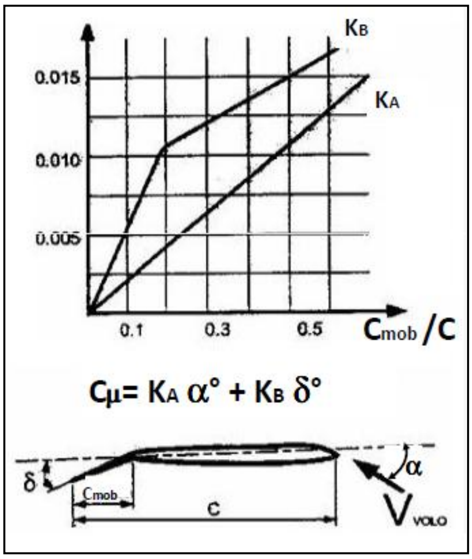

Figure 11 Example of Hinge Moment of Flight Control Surface estimation

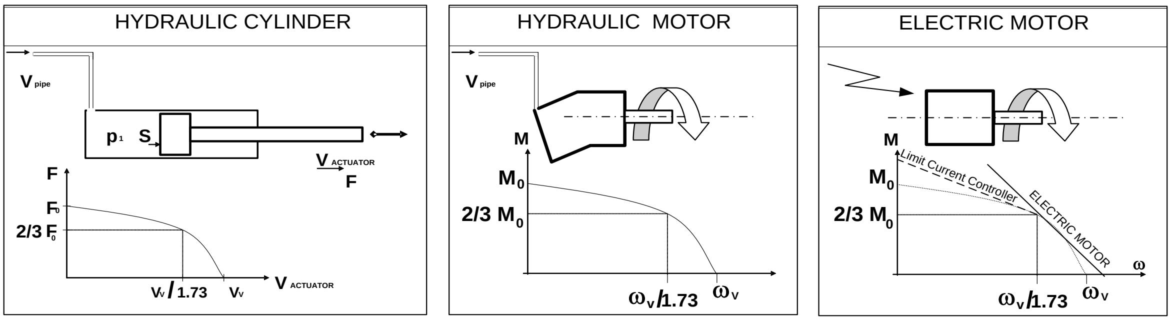

Fig. 12 Actuator optimal sizing [1]

Coming back to Figure 10, after all actuators have been defined as typology and sized (and this means to know the Power input needed too), the Operator will define which others Equipments, in particular Calculators and Control Devices (stick or column, pedals), are necessary; these, together with the actuators, will constitute the F.C.S. Main Equipments list. Then, as Fig. 10 shows, the procedure is the same already described for previous systems; choice of main equipments off the shelf or statistical estimation of their weights and volumes and electric power requested (for Computers and Actuators, if electric) and flow rate, at defined pressure, if Hydraulic Actuators have been selected. Obviously if the actuators are hydraulic a preliminary choice is the nominal pressure, if it is electric, preliminary choice is the kind of electric current and voltage.

2.4 Landing Gear System

The next System considered is Landing Gear, comprehensive of extension-retraction of Main Landing Gear elements and of Nose Landing Gear, of wheels brakes and of Nose Landing Gear steering. The approach, shown in Figure 13 is extremely similar to the one seen for F.C.S. as, also in this case, the Actuators are the core of the System. Also in this case many data, in particular geometry of Landing Gear and mass of relative elements could be already available; if not the Data will be introduced as input by the Operator. On the basis of such data ASTRID will estimate maximum loads (to be considered as "Stall condition" for the actuators), and these with relevant requirements of "No Load Rate", will allow to size the actuators with the already considered procedure summarized in Fig. 12. Then, as seen for FCS, the Actuators, i.e. the Main Equipments, will be selected off the shelf or statistically defined as concerns weight and volumes and the Power requested (it could be Electric or Hydraulic), when running, will be stored.

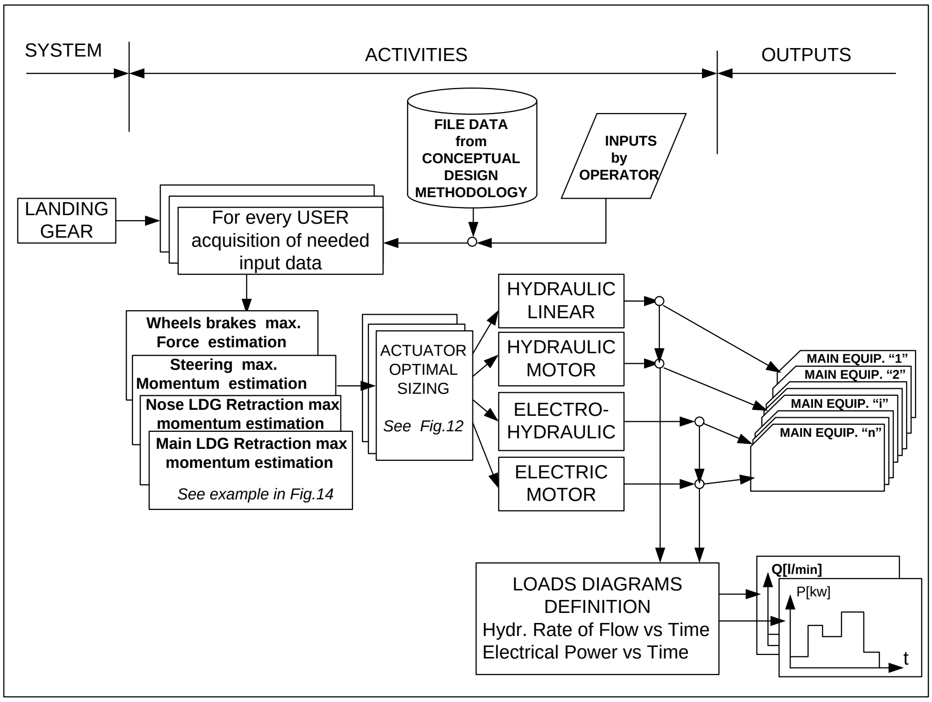

Figure 13 Landing Gear System definition, at conceptual level.

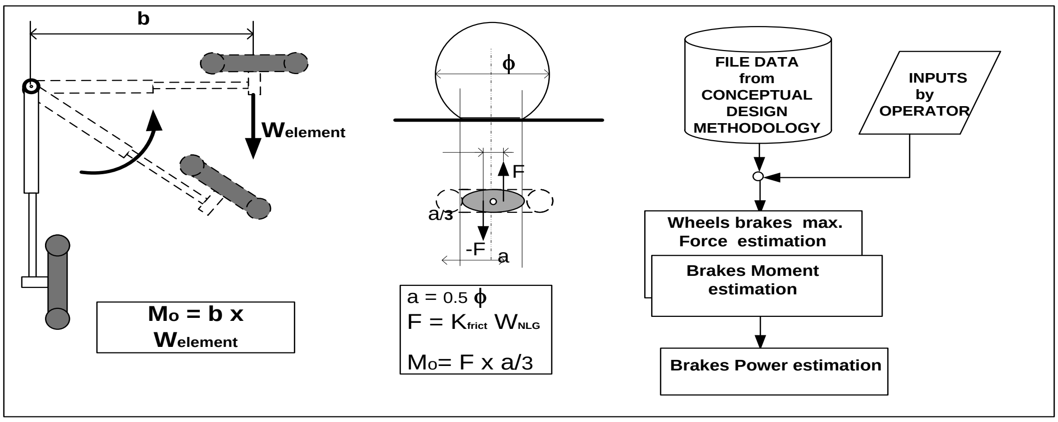

Figure 14 Calculations of Stall load for Retraction, Steering and Brakes actuators

2.5 Fuel System

The next System considered is Fuel System; this system, in particular as concern shape, size and location of fuel tanks it is strictly related to Airplane Conceptual Design, as the great volume of fuel to be hosted on boar is a strong constraint on Aircraft Design. By the way, in a traditional approach to Conceptual design of the Plane it is possible that the only value available is the total fuel weight, or volume. In this case, ASTRID will provide, obviously by input of Operator, to define the configuration of the tanks, by introducing the information shown in Fig. 15. Then, into the tanks, the Operator will locate the booster pumps, taking decision about redundancies, if it is considered suitable, and establishing, for each pump, the request performances, i.e. maximum and minimum flow, with the length of the line with the eventual difference of altitude Δz. On these basis ASTRID, by evaluation of loss of pressure along the line and considering the Δz, for each pump defines, in a diagram Flow-Pressure, the field of acceptability of Characteristic Curve of a Pump; in this way, as shown in Figure 15, the more convenient pump will be chosen. Please note then the several Pumps usually present in a System will have different requirements, so, after all pumps are defined it is necessary to unify the choice on the more critical one.

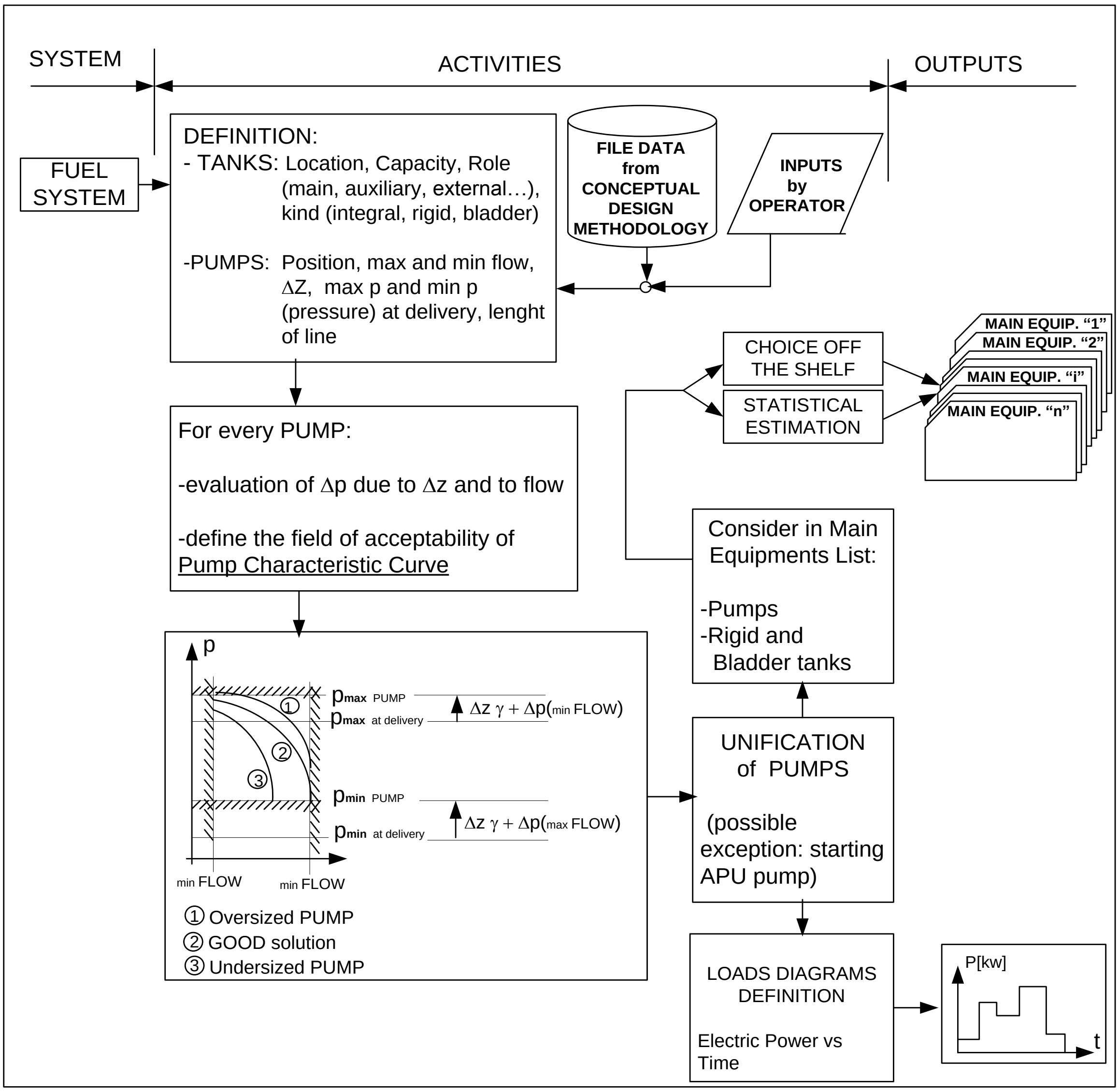

Figure 15 Fuel System definition at conceptual level

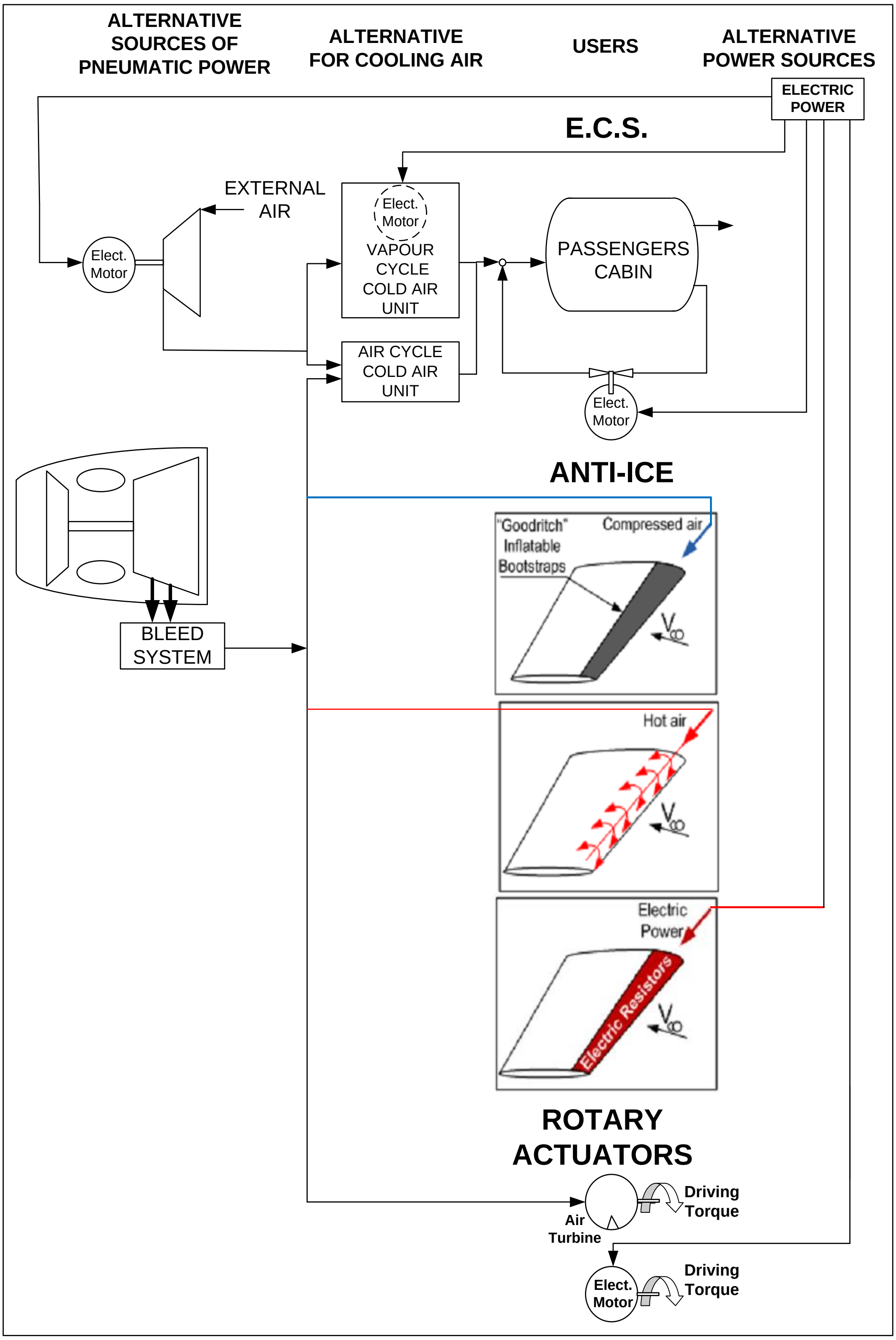

Figure 16 Pneumatic generation, E.C.S., Anti-Ice, Actuators

At this point the Main Equipments List (Pumps and Tanks not integral) is defined and the procedure become the usual; also the power requested by the fuel pumps is stored (with specification of kind of electric current and voltage).

2.6 Pneumatic generation, E.C.S., Anti-Ice, Actuators.

This field of On Board System is probably one of the more affected by new trends, and with interesting new solutions; so this section of ASTRID is quite complex in order to be able to face innovative solutions as well as more traditional configurations. Figure 16, in particular, shows how Pneumatic Power can be obtained:

a) By bleeding a small percentage(from 2 to 7 %) of air flow passing through the engine compressor; Fig. 16 reminds that, generally, the bleed is made of two different stages of compressor, and bleed flow is regulated in pressure and temperature.
b) By compressing external air thanks to compressor driven by electric motor.

The bleed has been, practically till now, the usual way to obtain Pneumatic Power, that can be utilized:

- To feed the Environmental Control System– E.C.S., thanks to the bleed pressure that allow to enter in the pressurized cabin, in order both to refresh the cabin air, and to control the temperature; obviously, as the bleed temperature is quite high, a passage through a Cold Air Unit is mandatory. In Fig.16 it is shown the modern solution of recirculating part of the air in the Cabin, so that the new air arriving from bleed can be colder and in reduced quantity; the reduction of bleed is clearly of advantage in saving fuel.
- To perform Anti Ice function, in particular the protection of wing and empennages leading edge; as Fig.16 shows the Anti-Ice actions can be made by utilizing the high temperature of bleed air or by utilizing the pressure in boots, installed on wing and empennages leading edge, that sequentially inflated and deflated, permit a mechanical de-icing.
- To feed Air Turbines that produce Driving Torque, i.e. transform Pneumatic Power into Mechanical Power, that allows to define them as “Pneumatic Rotary Actuators.

The great disadvantage of the bleed is related to fuel consumption and to ecological issues related to the remarkable waste of energy related to the fact that, quite always, because of the engine running at given rate, the pressure of bleed is higher than necessary for the users. This explains the idea of recirculating part of Cabin Air to reduce bleed utilized by E.C.S.

These considerations recently suggested (First application is the new Boeing B 787 [16]) the solution so called “bleedless”, in which pneumatic power is obtained by compressing external air with a dedicated compressor driven by electric motor; in this way we will have enough pressure for ECS, but not an excess. Fig. 16 shows that the necessary reduction of temperature for E.C.S. can be obtained by two different kinds of Cold Air Unit;

a) The Air Cycle Machine, in which the temperature reduction is achieved mainly by expansion of the air; so the air entering in the Air Cycle Machine must have a Pressure sufficient to have correct expansion and maintaining a level allowing to enter in pressurized cabin.
b) The Vapour Cycle in which the temperature reduction is obtained by removing heat from air thanks to the evaporation of refrigerant fluid, then compressed and condensed to continue the cycle; please note, the air to be cooled may have only enough pressure to enter in pressurized cabin (so lower than the pressure needed by Air Cycle Machine) but with the necessity of electric power for compressor that maintains the refrigerant fluid cycle. The low pressure requested for the air incoming is an energetic advantage not utilized in case of bleed but relevant in the case of dedicated compressor that can be less powerful.

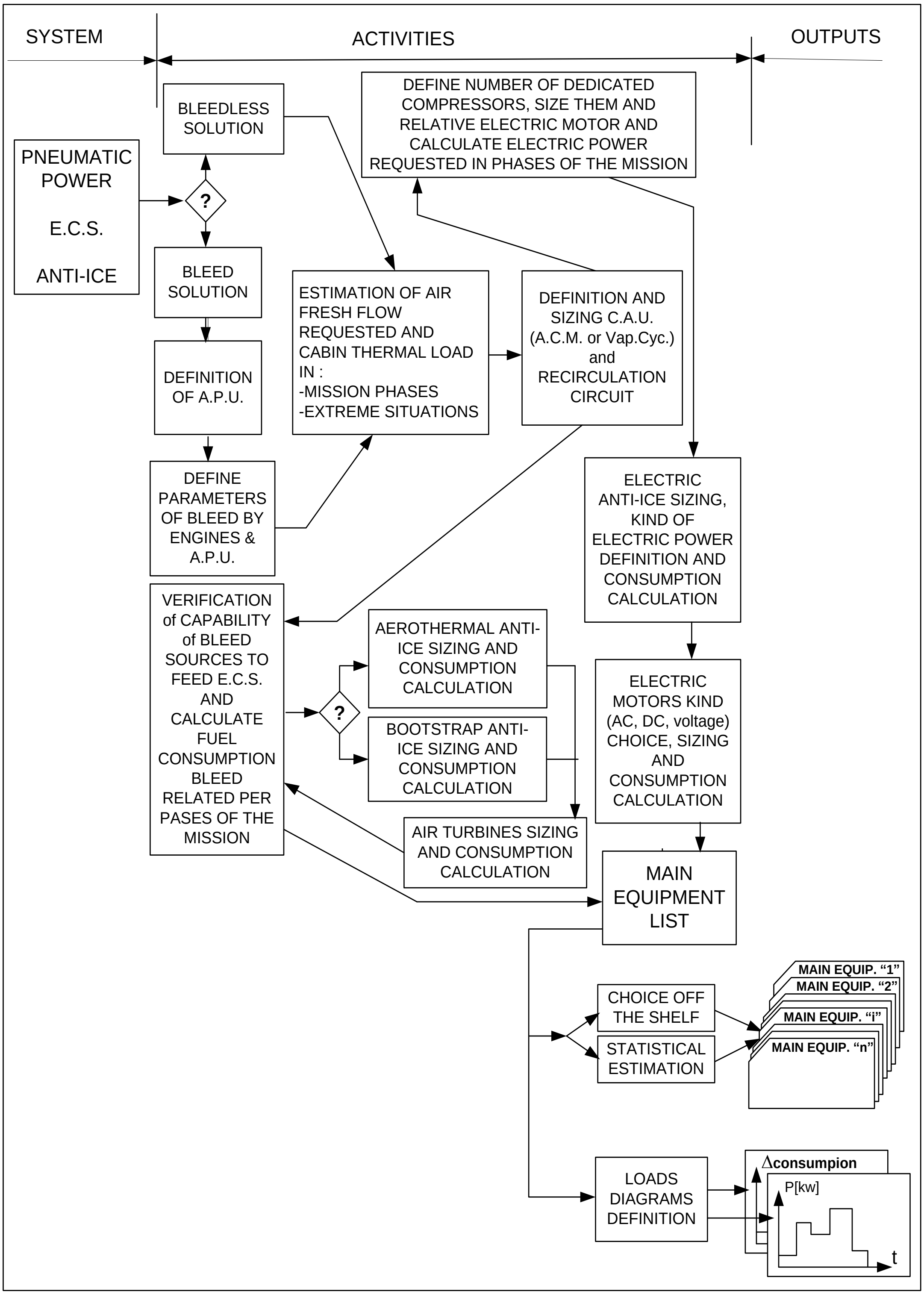

Figure 17 Pneumatic Power Generation, E.C.S., Anti-Ice & Actuators definition at conceptual level

In case of adoption of "bleedless" solution the advantage of avoiding energy waste of bleed is considered the increasing of electric power utilized; so bleedless is directly linked to more electric or all electric configuration; this explains as in Fig 16, in case of dedicated compressor to feed E.C.S., the anti ice and actuators are certainly electric and no more pneumatic.

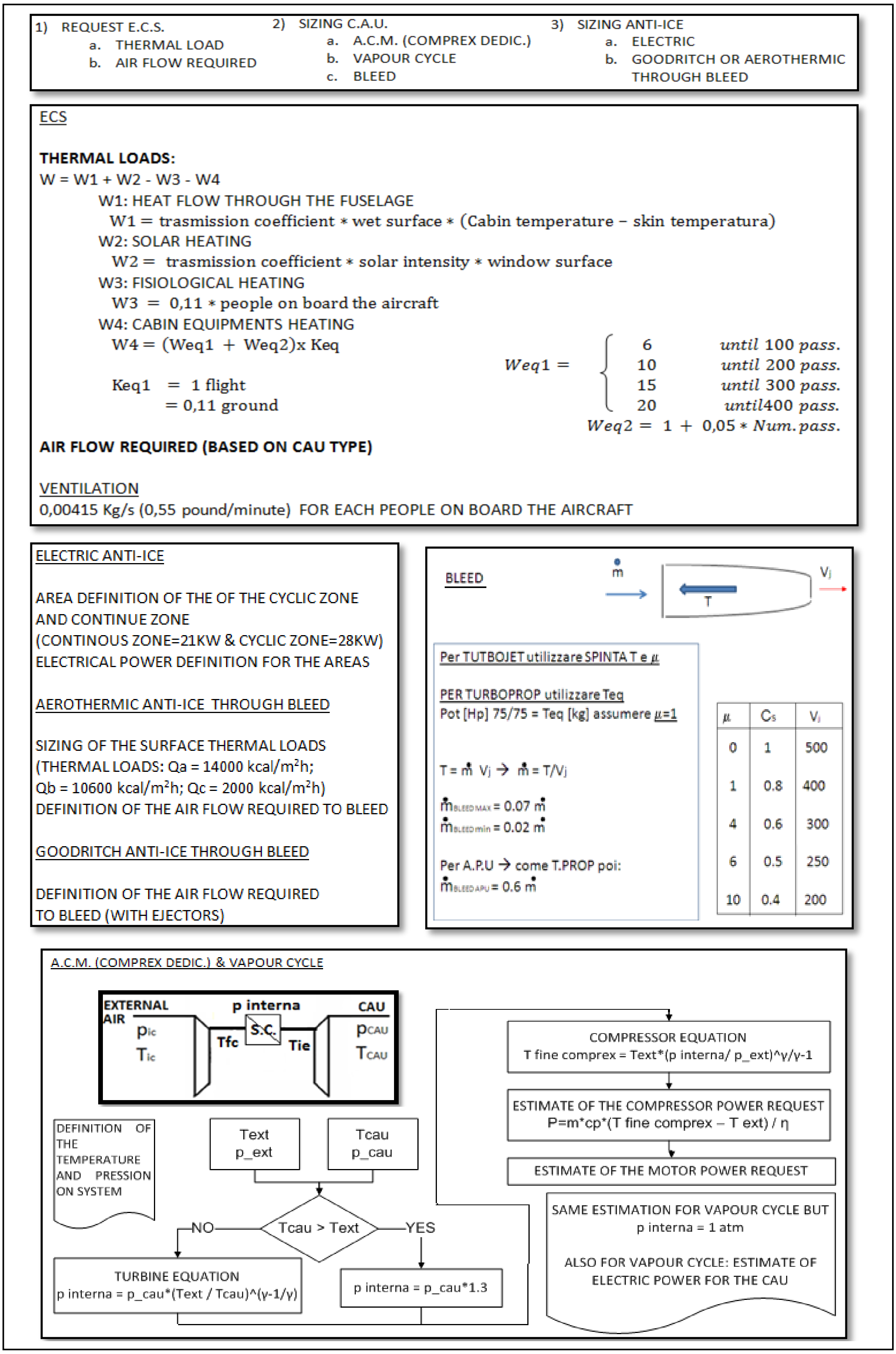

Figure 18 Pneumatic Power Generation, E.C.S., Anti-Ice & Actuators preliminary sizing relationship

Please note that electric feed is requested for some devices even in case of traditional configurations (i.e. with bleed), for example the feed of electric fan for air recirculation in E.C.S. or, in the Anti-Ice to protect propeller blades and small instruments like Pitot, in which electric devices do not have alternatives. On the basis of aforesaid considerations, in Figure 17 it is shown as ASTRID considers Pneumatic generation, E.C.S. and anti-ice, with possibility, at first, of choosing between traditional bleed solution and innovative bleedless configuration. As the whole topic examined is quite extended, to be brief in Figure 17 general strategy is reported and the relationships utilized are reported in Figure 18.

2.7 On board Power

This section of ASTRID is devoted to the System that are charged to feed all other On Board Systems; in the present case an exception is the Power constituted by "bleed", if it is present, that has been already discussed in previous point, in which, we remember, it has been discussed as it can be feed E.C.S., Anti-Ice and Air Turbines actuators.

Another System that can feed other devices, already considered, is the Hydraulic System, which task is to feed the actuators, in particular the ones of F.C.S. and of Landing Gear System.

As the topic of "On Board Power Generation" is, at the moment, in phase of great innovation, in Figure 19 possible general configurations, both representative of the state of the art, and of new trends, are shown. In particular, considering both the State of the Art, in which Hydraulic System is certainly one of the more relevant aircraft System, and the new trends, in which a form of Hydraulic System, fed by the Electric one, is possible, a first part of this section of ASTRID is dedicated to Hydraulic System; obviously this part will not be used if a complete adoption of the trend to "All Electric" occurs.

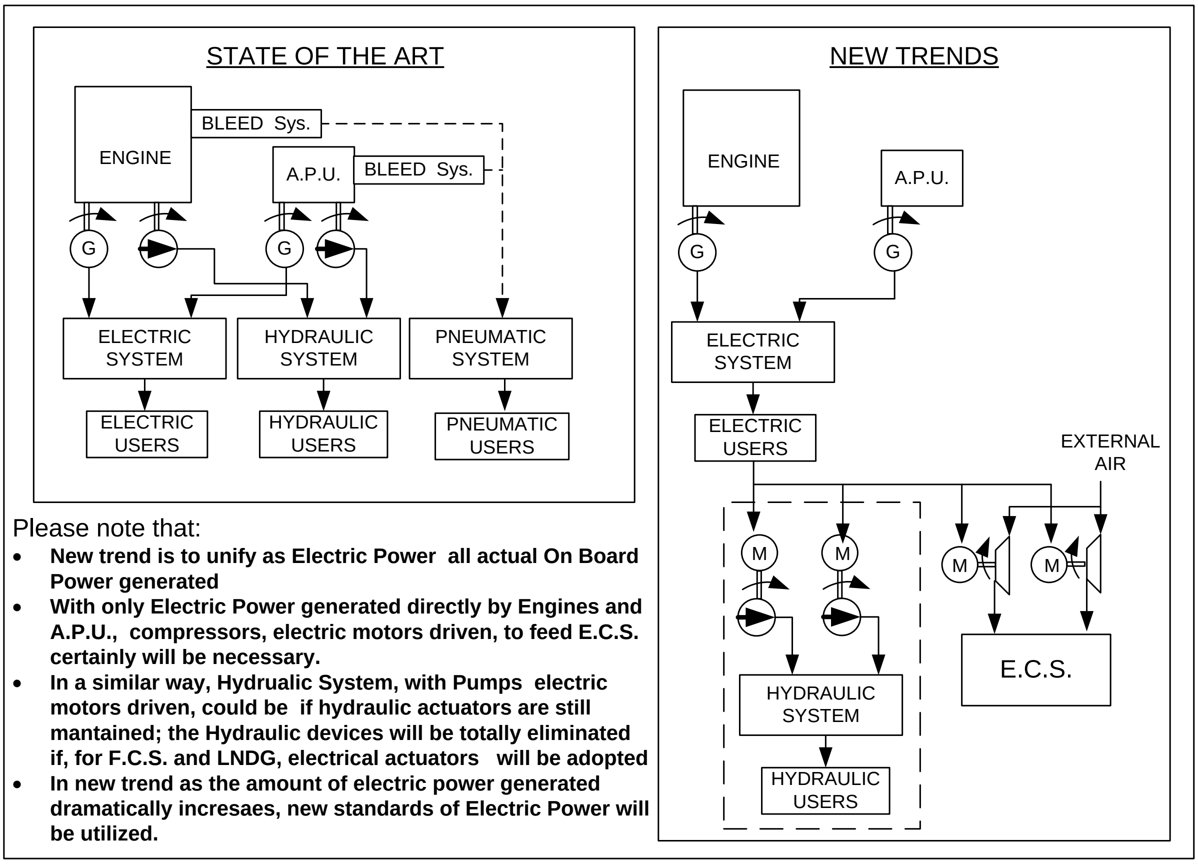

Figure 19 State of the Art and new trend in Power On Board generation

Figure 20 illustrates how ASTRID manages, if present, the Hydraulic System; the more relevant task is certainly to size pumps, that means to find the pump characteristics, in terms of pressure and of deliverable flow to be compared with Flow needed at every phases of the mission, i.e. the so called "Load Diagram". As shown in the Figure we have two different cases:

a) The Pump is mechanically driven by an Engine; in this case it is to be considered that the Flow deliverable by the pump will change when the engine rotational speed changes, and the nominal flow of the pump will be obtained only when the Engine runs at his maximum rate. So, in load diagram the "available Flow" will be a function given by Nominal Flow by ratio of actual engine rate to maximum engine rate. The sizing of the pump is to find the minimum Nominal Flow that allows, in every phase of mission, that available Flow is greater than Needed Flow.

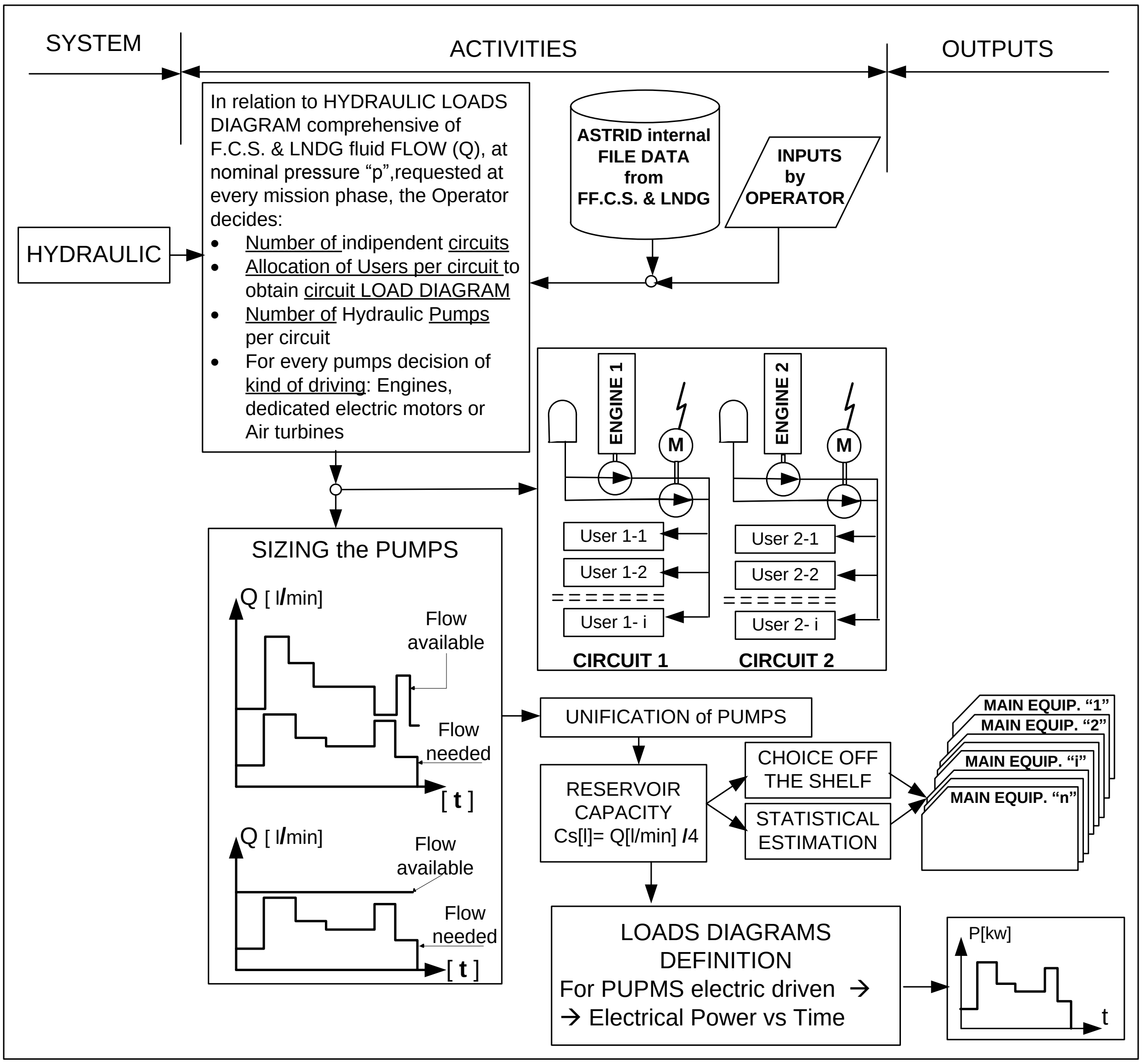

Figure 20 Hydraulic System definition at conceptual level

a) The pump is driven by a dedicated motor; in the actual State of the Art the motor could be an electric motor of an Air Turbine fed by bleed (see previous point 2.7), with new trends certainly an electric motor. As shown in Figure 20, in this case the Pump could always offer his nominal Flow, so in the Load Diagram it will be a constant value that in every phase of mission must be greater than Needed Flow.

Please note that the ASTRID procedure, we are explaining, will be repeated for every Pump, so it will be possible to consider the presence of both kinds of Pumps, engine driven and dedicated motor driven. Obviously for every circuit, in case or more than one pump, it is practically obliged that this is a redundancy; in this case if the pump are of the same kind, only one has to be sized.

Figure 20 shows that, after all Pumps has been sized, a unification is needed on only one kind of Pump (could be two in case that both kind of pumps, engine driven and dedicated motor driven, are present.

Also the Reservoir (one per circuit) can be preliminary sized; in Figure 1 an empirical, experience base, criterion is proposed,

Considering Reservoirs and Pumps the Main Equipment that at this phase is possible to define, the usual procedure for such Equipments definition is utilized. Relevant the necessity, in case of pumps driven by electric motors, of storing the Electric Power requested, at every mission phases, to utilize them in the next Electric System definition.

Passing now to consider Electric Generation it is clear that this one will be always present, and, in particular by thinking about new Trends, it could be the unique source of Power On Board (it is the case of All Electric, or even in the case of Hydraulic System still present but completely Electric driven; by the way ASTRID allows to study such situations as well as the traditional solutions with, in addition to Electric System, an Hydraulic and/or a Pneumatic System, based on "Bleed".

Figure 21 shows the two more relevant architecture for Electric Generation, still largely adopted in Airplane at state of the Art.

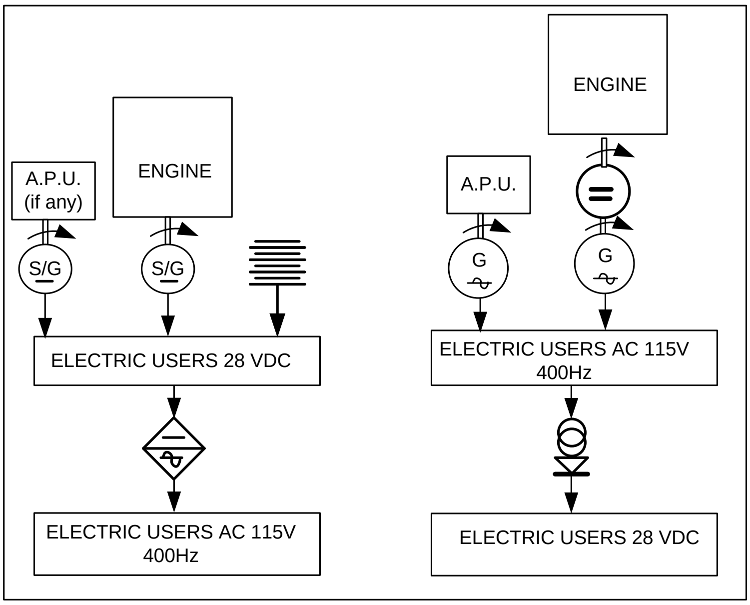

Fig. 21 Electric Generation: State of the Art configurations

The first is based on generation of DC at 28 V, with generators mechanically driven by engines; a part of generated power is transformed by mean of Inverters in Alternate Current at 1115/200 V with frequency of 400 Hz, to feed the users that needs this kind of Power.

To minimize the size of the inverter (and its losses) all users that can be fed by generated current will be in 28 VDC. The problems of this configuration are the low Specific Power due to the fact that great part of the System has low voltage and the fact that the Generators are brushes; by the way this aspect of Generators offers the advantages that they can be utilized, fed by the battery, to start the Engines, so that they are known as Starter/Generators. The use as Starter is possible, without oversizing the electric machine as generator only for small dimensions, i.e. for airplanes like trainers, executives, small turboprop transport (this explains why in the figure the A.P.U. is considered optional), always with small turbo-engines.

The second configuration useful for all other kinds of planes, removes the problem of the first by generating AC that, on the base of Unification established in 1951 can have an higher voltage of 115 V (or 200 wit “Delta” connection). Like in the other solution a part of Users need different kind of Current, so Transformer Rectifier Units -T.R.U.s convert part of generated AC in 28 VDC. The generators are clearly “Alternators”, that are “brushless” machines, but without possibility of starting (usually, in state of the art of airplanes the starting of Engines is demanded to Air Turbines fed by bleed of A.P.U., that is a turbo engine so small to be started electrically by battery). Another problem is to stabilize the frequency in view of variable rotational speed of engines (no problem for alternators driven by A.P.U. that run at constant rate); the usual solution has been (and it is still today largely diffused) the adoption of Constant Speed Driver –C.S.D. i.e. a mechanical-hydraulic equipment that, receiving in input the variable angular speed of the engine, is able to drive at constant speed the alternator. Even if C.S.D. has been e great success with practically generalized adoption, it is expensive and, that is its greater defect, with not high reliability. The success of C.S.D., in past half century, is due to the inadequate of Electronic Technology in Power Supply that made inacceptable a wide frequency for a lot of kind of users. Now the situation is completely changed and for example the AIRBUS A 380 generates 115/200 VAC wide frequency, with great advantages in comparison to the classic solution with the C.S.D.. It is of interest the consideration that the progress in Electronics offered another interesting alternative to C.S.D., that is Electronic Power Converter - E.P.C. that, receiving in input VF from the alternator, supplies 400 Hz to the users, as shown in Figure 22; obviously this solution (certainly less expensive and more reliable than the solution based on C.S.D., has to be compared with the aforesaid solution of generating wide frequency (please note that of many users this is not a problem) with enhanced power supply devices for user that cannot accept directly the VF. The former solution seems now to be preferred.

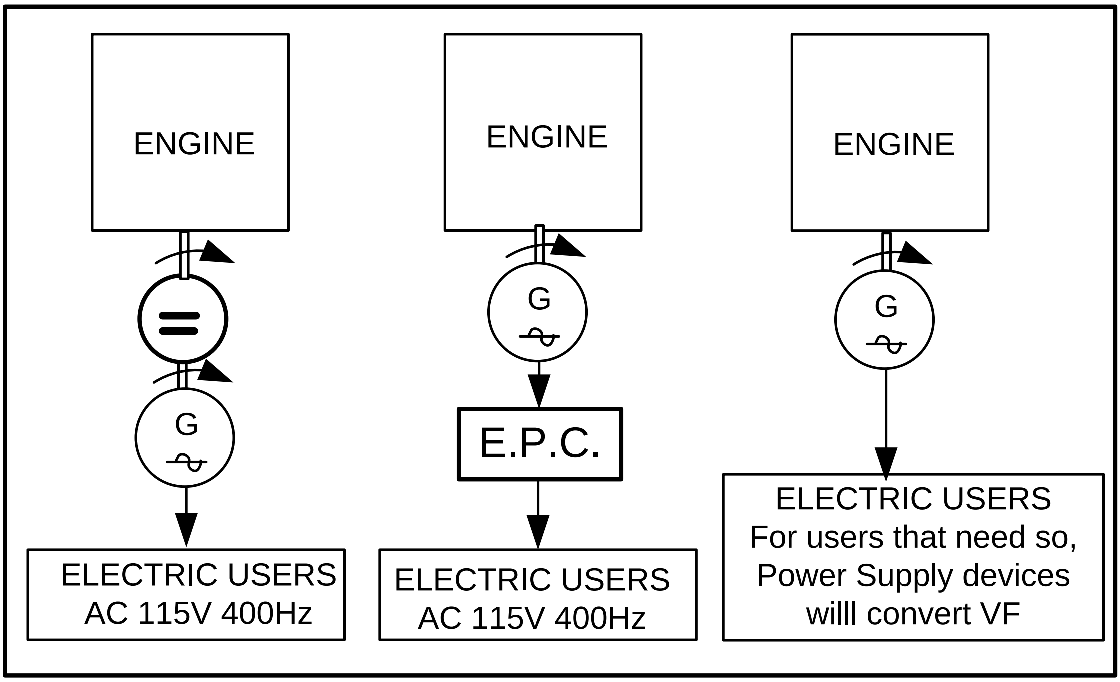

Figure 22 Solutions to the problem of Variable Frequency -VF

So in order to allow ASTRID to treat also the more advanced configurations, some considerations on new electric generation Systems has to be done. Certainly the electronic progress is a key factor for the adoption of all electric technology; the consideration now discussed above the problem of VF, as well as the realizations of actuators with accuracy in positioning control not less than Hydraulics one. Another aspect to be underlined is that the greatly growth of electric power generated on board promoted the adoption of new standards for electric currents. In particular, thinking to feed actuators a new High Voltage Direct Current –HVDC was established with the value of 270 VDC. With such a high voltage clearly a brushless configuration was mandatory and, at the moment, two solutions have been proposed:

a) The Switched Reluctance Machine –SRM [17] that is based on idea to have an Electronic Control Unit that by switching sequentially couple of opposite coils on the stator, in function of the angular position of the poles of rotor (that is not a magnet and is without coil, having the only function of creating a magnetic circuit), drives this one to rotate, as the Figure 23 shows. This machine is reversible so that it can act as Starter/Generator. It has been adopted for new fighter F 35.

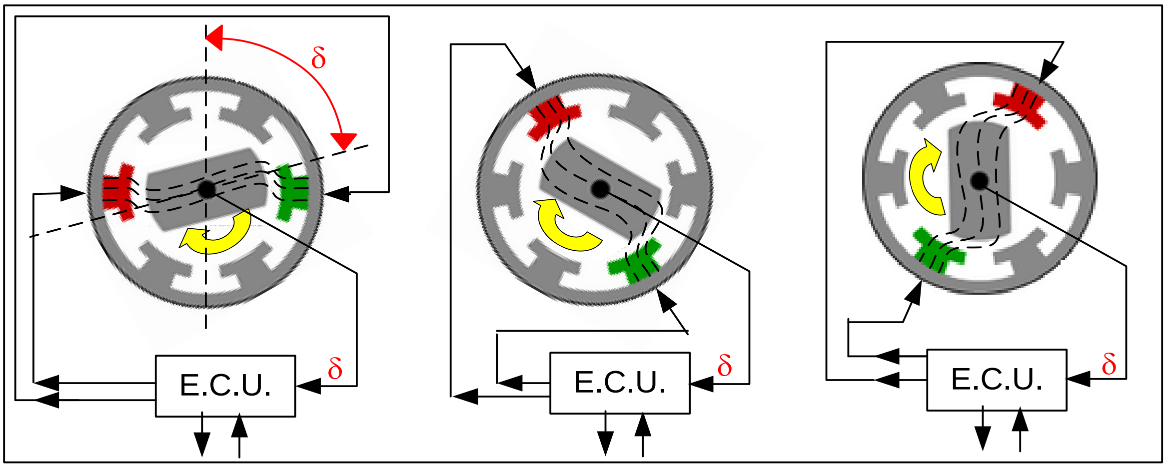

Figure 23 Switched Reluctance Machine –SRM (schematic)

b) A Permanent Magnet –PM alternator with a power converter that can be bidirectional, i.e. receiving 270 VDC the Generator becomes Starter. Please note that to make easy to obtain the voltage of 270 an optimum value for alternator is 235 V.

Taking in mind the considerations made before about the recent interest in Variable Frequency, a further idea is to utilize the alternators to produce AC at Variable Frequency and then to convert only a part of them (not the part consumed by users that can be fed in VF) in 270 VDC, in 115/200 VAC 400 Hz and in 28 VDC. Please note that, thanks to a "Start Converter" the alternator maintains the functionality of starter (in this case it will run as a synchronous motor fed by the converters with frequency continuously adapted at the rotational speed reached.

In this case, for the above said easy conversion from 235 VAC to 270 VDC, in addition to specific weight reduction of higher voltage, another new kind of electric current proposed is 235 VAC VF. This kind of current has been adopted in new Boeing B 787, like AIRBUS A 380 generates 115 VAC VF. In the Figure 24 are schematically shown the two solution based on generation of 270 VDC and the system based on generation of 235 VAC VF, taking into account the same architecture can be proposed with 115 VAC VF.

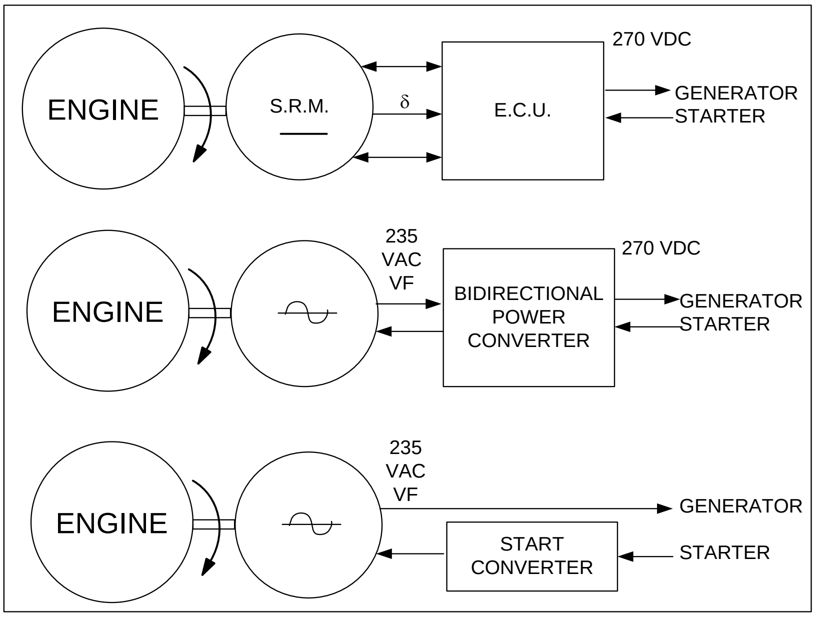

Figure 24 New kinds of electric generation

. Please note that this architecture is representative both of the case that the generator is SRM and Alternator with output converted. Please also note that, if it is necessary, the architecture could be utilized to represent a generation 28 VDC (like the case of Figure 21), by changing class of generators and considering as the only converter the one to 115 VAC 400 Hz.

The second architecture is representative of the generation at VF, with all the possible kinds of converter considered, in particular the two of the previous case plus the conversion of generated AC VF into 270 VDC. Obviously, only with the change of class of generators, the architecture can represent the case with generation of 115 VAC VF., as well as, always changing class of generators plus considering only the converter to 28 VDC, the second classic configuration (Figure 21) can be represented.

Please note that basic architecture allows to consider whenever number of engines (in Figure 25 they are two, but it is possible to consider more as well only one) and A.P.U.. In the Figure it is shown the case of one Generator per engine and A.P.U., but it is easy to consider redundancies. As shown in Figure 25 the part of power requested in 28 VDC, that is to be considered “Vital”, can be defined to allow to verify that emergency battery is adequate.

Passing to Figure 26, the procedure to define the Electric System is here presented: at this moment, in particular in case of adoption of “All Electric Philosophy”, all data about Electric Power requested, by all other Systems and for every phase of the mission are to be recalled; if not already defined, obviously they will be defined as inputs and could be, at this moment, not so good as they seem when they were decided; this is a usual practice of design that, at every moment of its development, may evidence the opportunity of feedback on previous decisions.

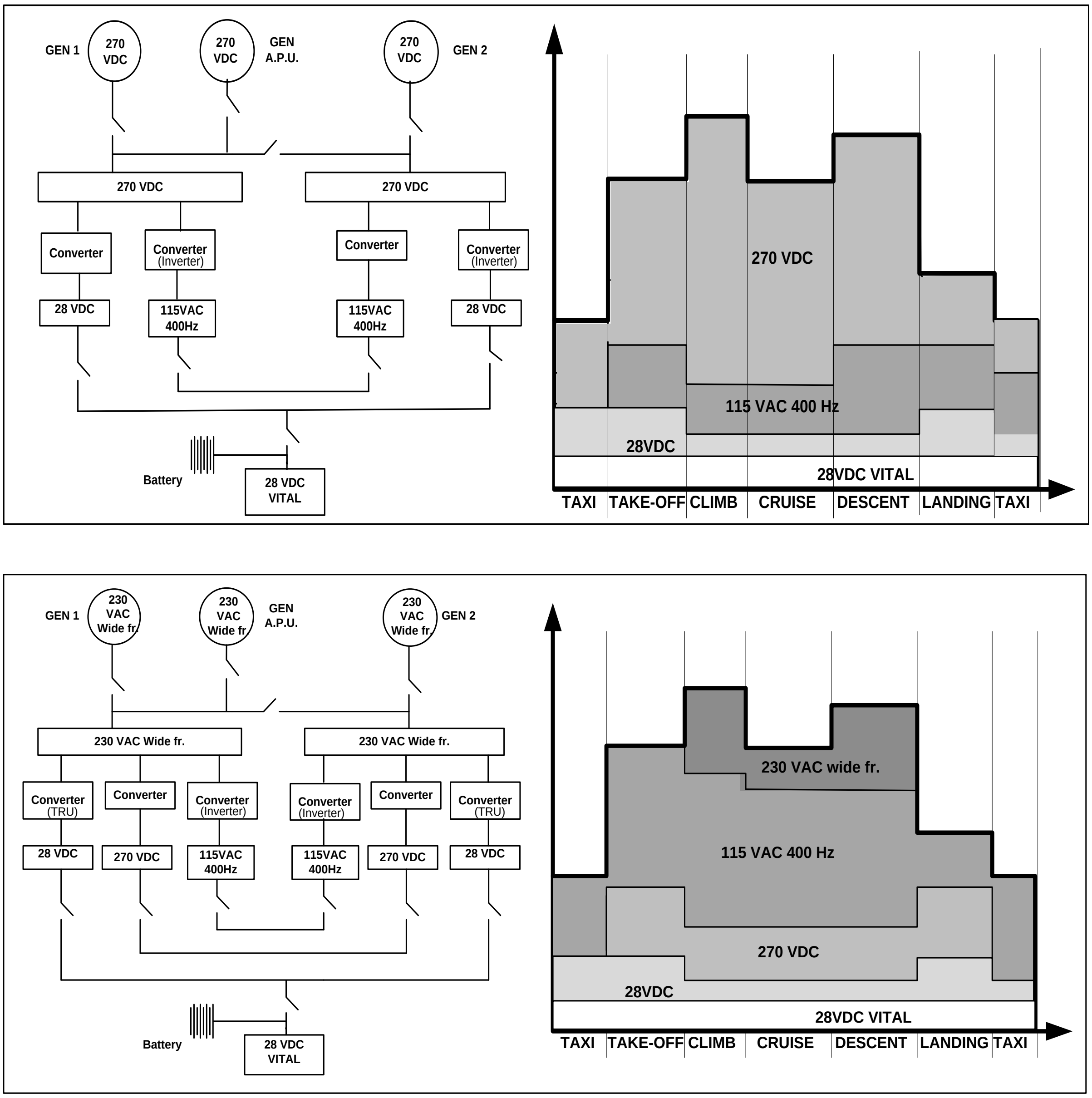

Figure25. Electric System: examples of schemes and Load Diagrams for 270VDC and 230VAC VF, from [1]

ASTRID, as already said, offers a guideline in defining the architecture of the system, in particular through the steps shown in Figure 26. In this way the Operator will arrive to have the bloc diagram of the whole System and the list of Generators (with kind defined too) with, for each one the knowledge of P.C.s fed and the Load Diagrams of P.C.s and the total of Generator (in which the Load Diagrams of P.C.s enter as addenda. Having for every equipment (Generators and P.C.s) the relative Load Diagram, it is easy to size them and, only for generators, to account the fuel consumption caused by On Board Generation.

After sizing of Generators and P.C.s it is necessary to unify the size of various equipments.
In addition to other Equipments like batteries, auxiliary generators (for example driven by a R.A.T.) the Main Equipment List is completed and as usual such Main Equipments will be found off the shelf, or statistically defined as weight and volumes.

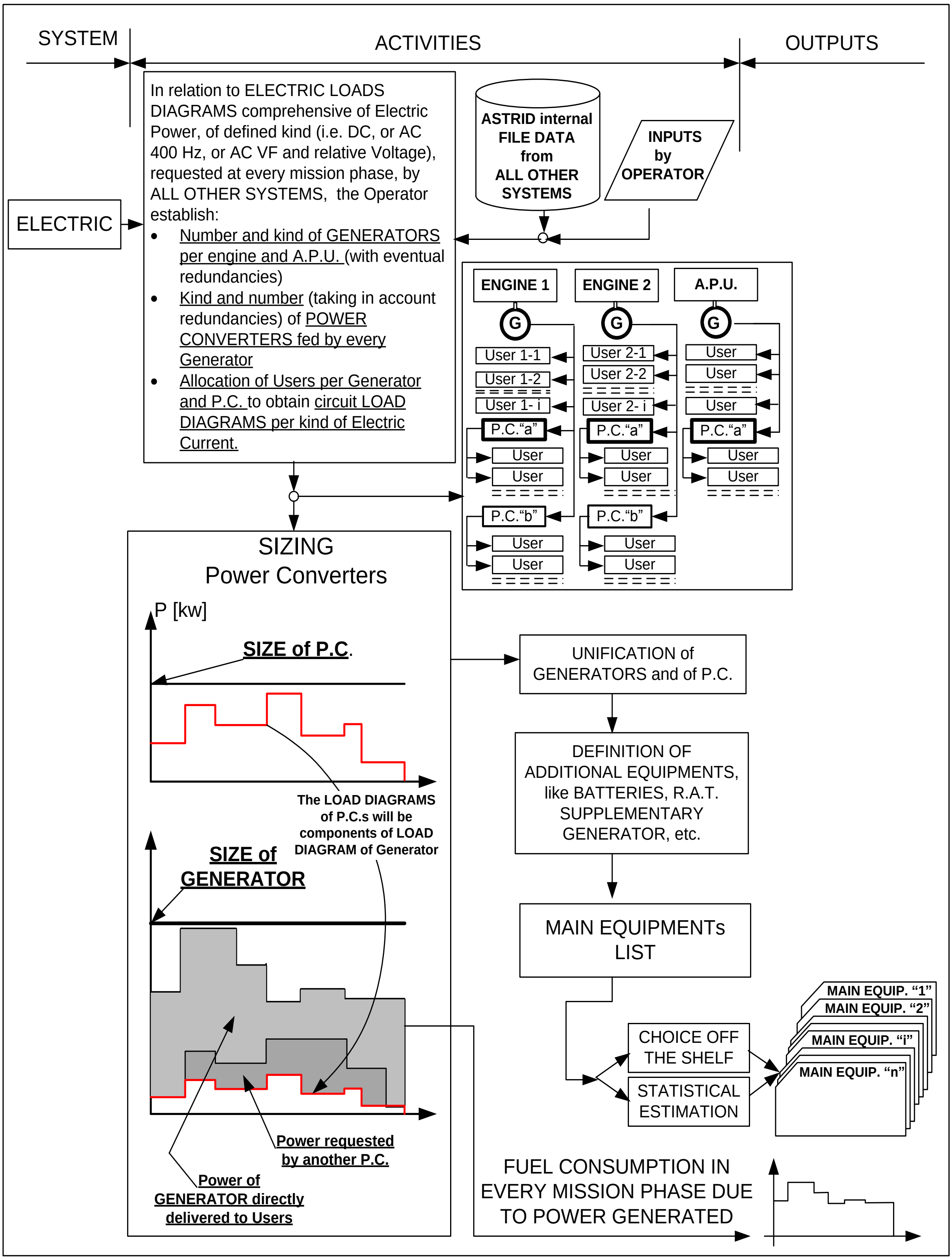

Figure26. Electric System definition at Conceptual Level

2.8 Engines and A.P.U. starting functionality verification

After completing the considerations about the various on board Systems and how they can be defined, some conclusive verifications are needed. In particular the functionality to have a staring procedure, fully autonomous, is today strongly needed. How an autonomous starting can be obtained is a quite complex problem in On Board Systems, with dramatic changes introduced by new trends more or less connected to “All Electric Philosophy”. As already observed in Figure 21, in the State of the Art, electric starting of Engines was adopted only in small airplanes with turbo-engines, with generation of 28 VDC; for all other kind of planes, with generalized generation of AC 115/200V, the start of engines was assured by Pneumatic Starters, i.e. Air Turbine Motors mounted on engine gear box [18]. The autonomy of “self starting” was, for these kinds of Planes, assured by a two steps procedure:

a) Starting of A.P.U. that as it is a small turbo-engine so it does not have problems to be started by electric starter fed by battery
b) The A.P.U. bleed feeds the pneumatic starter of the engine.

Please note that now both these kinds of engine starting are no more suitable as the electric machines with brushes are no more acceptable, for the first case, and the pneumatic system based on “bleed” is certainly no more acceptable as energetic efficiency. By the way the dramatic increase of Power generated on board trends to overcome the problem that in the past did not allow electric starting on great part of planes. Figure 27 shows the power generated on board by a single generator in function of Equivalent Thrust (as defined in Figure 18, in order to consider the turbo-prop too).

In the plot, for some planes the values of power of one Generator vs. the Engine Equivalent Thrust, are shown; it is to be noticed that to specify “ one Generator”, even in the case of two generators on one engine (it is the case of B 787) it is specified that the starting must be granted by only one electric machine; a starting with two starters running together can be, for such a plane, usual but the starting with only one starter in action is mandatory to have an acceptable dispatch Reliability. In the plot are reported data of the following planes:

a) Alenia-Aermacchi MB 339 basic trainer that is powered by a turbojet of 1800 kg with a starter-generator (we are in the case of Configuration 1 of Figure 21) of 12 kw
b) ATR 42, Regional Turbo Prop with two engines of about 1800 Hp, both with a starter-generator comparable to the one of previous airplane
c) The new fighter Lockheed F35 equipped by an engine with T= 12000 kg (without A.B.) and with starter generator that is a SRM of about 120 kw
d) The Boeing B 787, with engines with T=30000 kg and Alternators (Generators of AC 235 V, VF) of 250 kw

The four airplanes, as the plot shows, cover practically all the range that can be of interest to investigate today and in the next future. The four airplanes are all the electric engine starting (in Figure 27 they are marked in “green”), so the strain line in the plot can be considered as (conservative) envelop of the possibility of electric starting. This is confirmed by the fact that in the same plot also the correspondent data of some representative aircraft, covering all considered dimensional range (Alenia-Lockheed F104S, MDD DC10, AIRBUS A340 and A380) in which the engines are not electrically started are reported, (points marked in “red”), and, as it is easy to be noticed, all stay below the line.

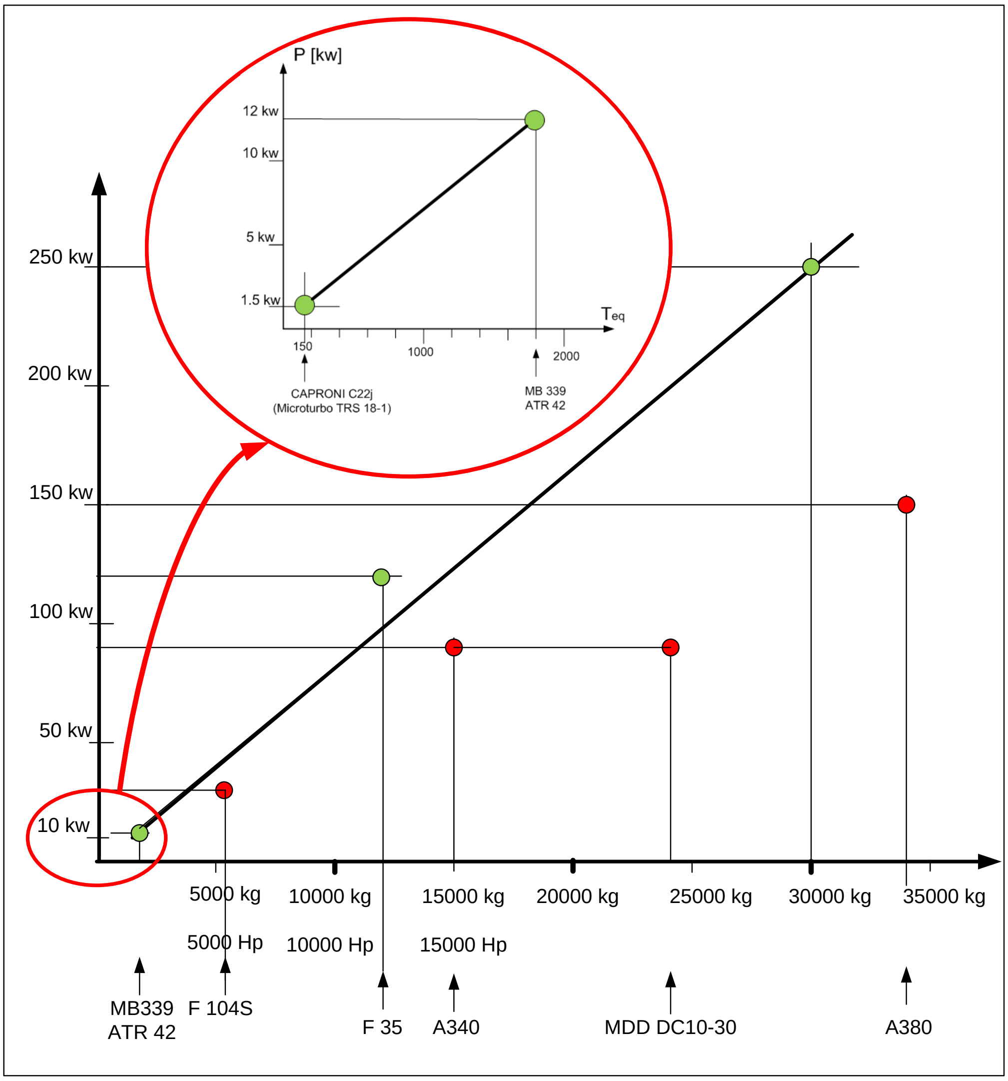

Figure 27 Electric starting capability vs On Board Power generated

Please note that in Figure 27 it is shown how in the field of small Planes (and engines) (smaller than the aforesaid MB 339 and ATR 42) the envelop can be defined by considering the available data of a very small turbo-engine and its starter-generator; please note that the extension to this field can be useful for verification of electric starting for A.P.U.s. So the envelope can be mathematically expressed as:

$P_G = 0.00634\ T_{eq} + 0.59$ for $T_{eq} < 1800$ kg (if Power < 1800 Hp)
$P_G = 0.00844\ T_{eq} - 3.19$ for $T_{eq} > 1800$ kg (if Power > 1800 Hp)

So, by checking that P_G, i.e. Electric Power of a generator driven by a turbo engine of thrust (or power) T_{eq}, is greater than value given by relationship above, the capability to perform the electric starter of the engine will be assessed.

2.9 Installation on Aircraft Module

This is last module of ASTRID and it is not possible to visualize it without a CAD-3D module to be interfaced; by the way it is to be considered [2] that an up to date Conceptual Design Methodology must have such a module. Purpose of this module of ASTRID is only to allow connection with CAD module to install the defined Main Equipments on the aircraft, with possibility of calculating contribution of the Systems to the CoG location and to the moment of Inertia values.

In order to offer a complete vision of ASTRID capabilities Figure 28 shows an example of preliminary installation of Main Equipments on Aircraft.

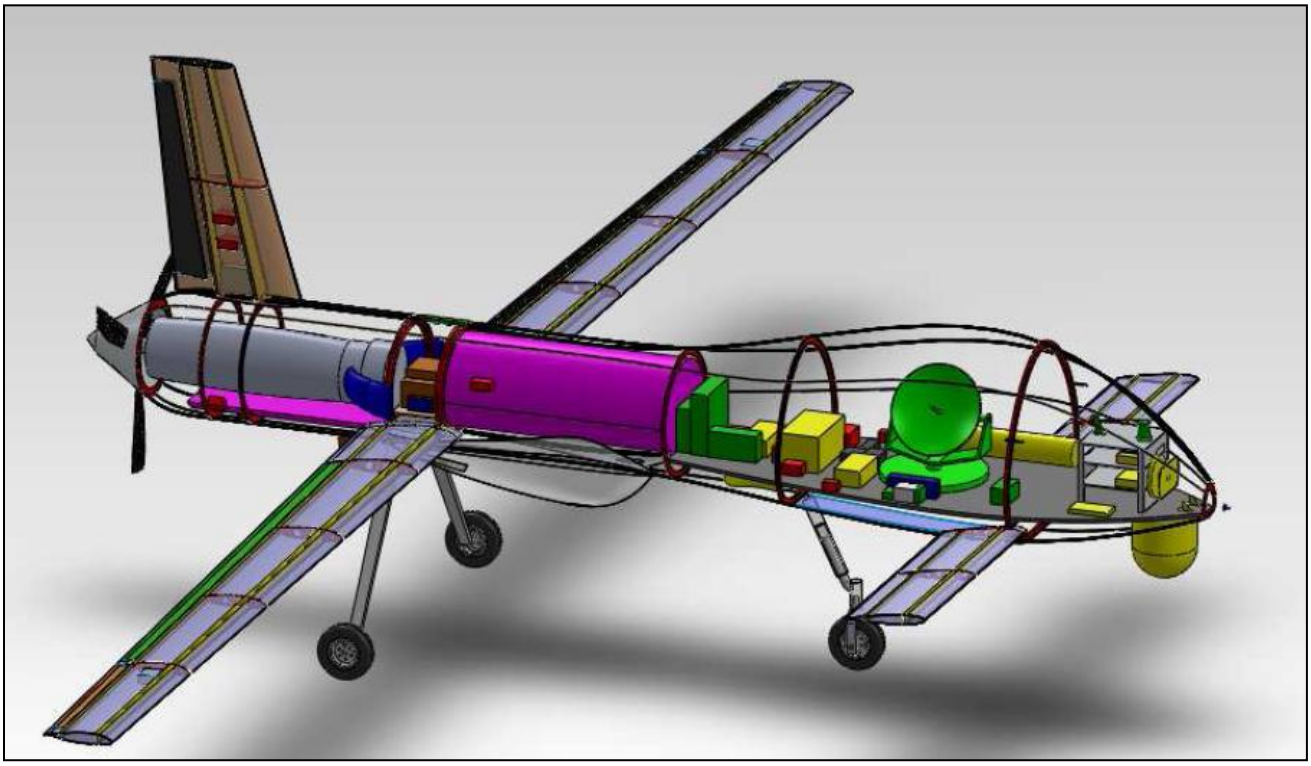

Figure 28 Example of installation on Aircraft of Main Equipments defined by ASTRID

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Acknowledgments

The Authors wishes to thank very much Alessandro Inferrera and Edoardo Santaniello, for strong work performed during preparation of their Master Degree Thesis in Aerospace Engineering at Politecnico di Torino.