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# Towards More Optimization for Aircraft Energy Conversion Systems

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## Abstract

This paper introduces the new challenges associated to the design of future energy conversion, storage, ejection hybrid system. The technological aspects of all sources and loads, including power electronics converters, have to be taken into account up to system level. The methodology proposed by a joint consortium between industry and academia is based on design by optimization. It will be illustrated using past examples. The optimization models requirements and the associated tools will be briefly described.

## I. Introduction

### A Aircraft Systems electrification context

The aircraft electrical system mission is to maximize the power availability with the required quality respecting the load hierarchy, be extremely safe, minimize its induced fuel consumption by means of a minimal power extraction for a given load configuration through high efficiency and smart peak power “shaving”, and by minimizing induced weight and drag due to electrification of power systems, including those due directly to the electrical system

This last point includes the minimization of the induced weight and drag of all “installed” electrical energy conversion resources, ranging from the generator (and the need for a gearbox) to the load side transducers. Aircraft electrical systems need also to be easy to install, to be maintenance free and have a minimum acquisition cost. Figure 1 shows the added complexity brought by the more electrified aircraft system trend on the electrical power system. Improvement of the electrical system in weight and size by itself will not bring significant improvement at aircraft level. In fact ACARE (Advisory Council for Aviation Research and Innovation in Europe) strategic research plan mainly focuses on flight physics, propulsion and structure as described in [1].

The use of combined electricity and thermal energy at the two main power vectors for “utilities” produces several improvements on the aircraft that would not be achievable otherwise. Optimal energy management is based on an all electrically powered system and electrification of power systems, including thermal management, leads to efficiency, availability, lower emission, and enables the use of composite materials for aircraft wings.

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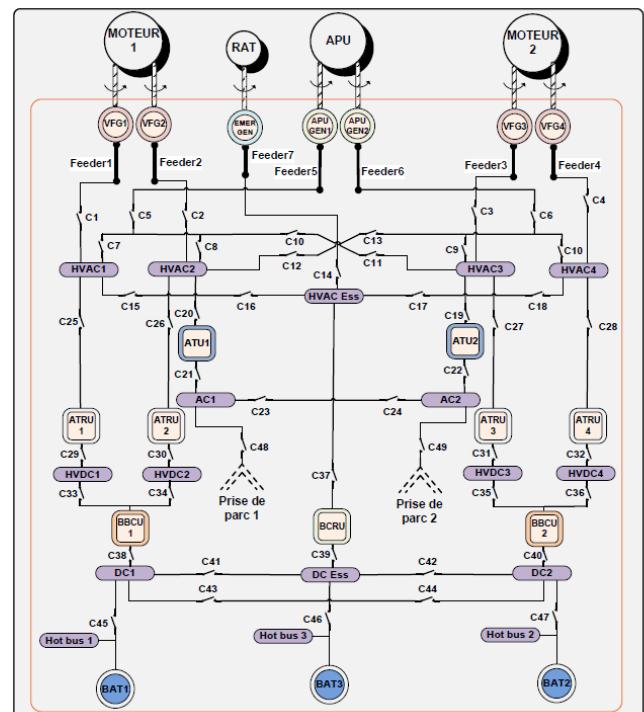
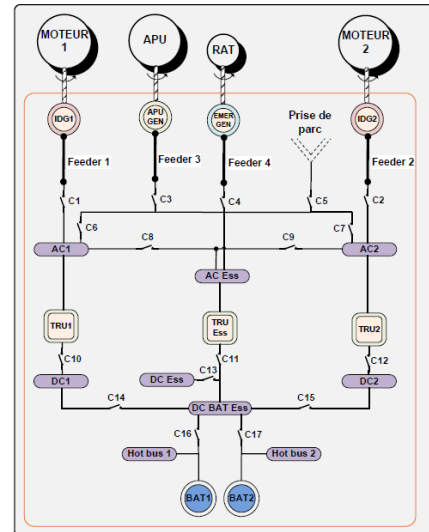


Figure 1 legacy bleed aircraft electrical system versus more electrical hybrid HVAC HVDC electrical system

E- Engine start, E-hydraulics gen, E-APU, E-Taxi, E-Brake, E-WIPS, E-ECS, E flight actuation are some examples of this trend. As shown in figure 2 [22], future aircraft will be more electrical, but the link with other systems is not only through electrical power: indeed, the intelligent load management requires data about load status, operating modes, characteristics, mission.

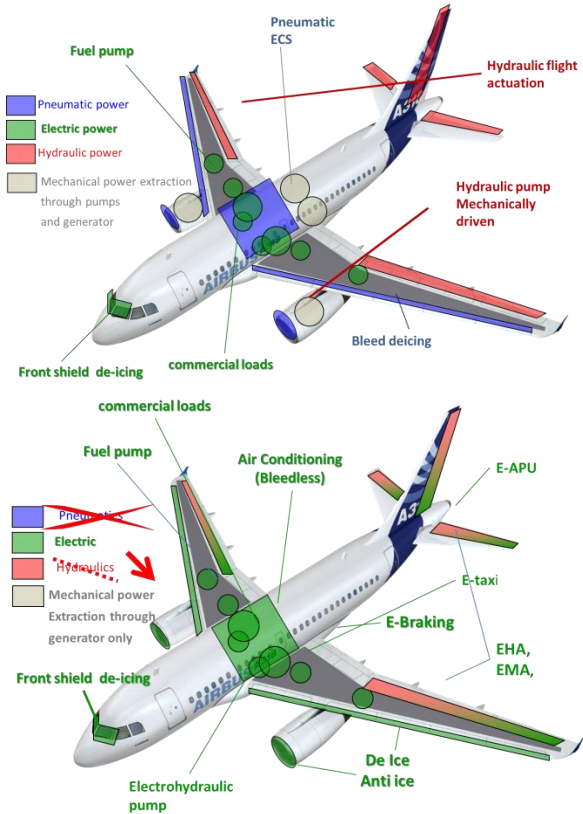


Figure 2. legacy power (top) and MEA power aircraft (bottom)

## B Need for a multidisciplinary optimization framework

As shown in figure 3 [2], aircraft power conversion systems have strong interdependencies with the engine and other aircraft systems. Therefore the design of the electrical system by optimization needs to be performed in conjunction with the other aircraft systems. A similar approach is currently used during the aircraft conceptual design phase; in fact MDO studies optimize jointly structure, aerodynamics and propulsion. What level of detail should be brought at aircraft level design? Do we need another MDO framework for power systems optimization using a surrogate model of aircraft and propulsion? This paper will try to answer these questions in the conclusion. in the meanwhile it needs to be underlined that the electrical system optimal design requires an integrated design process with other electrified power systems and taking into account engine and aircraft design characteristic's, mission and environment induced constraints and opportunities.

Figure 4 shows the complexity of interactions between the thermal management system and the other systems and the opportunity to optimize its electrification with EPS [62]

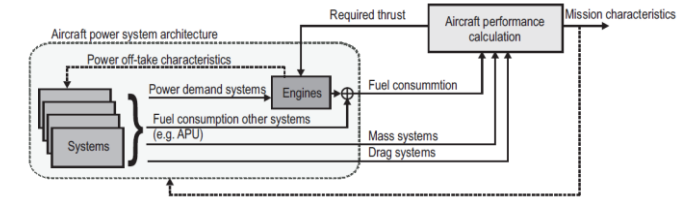


Figure 3. coupling between power systems and aircraft

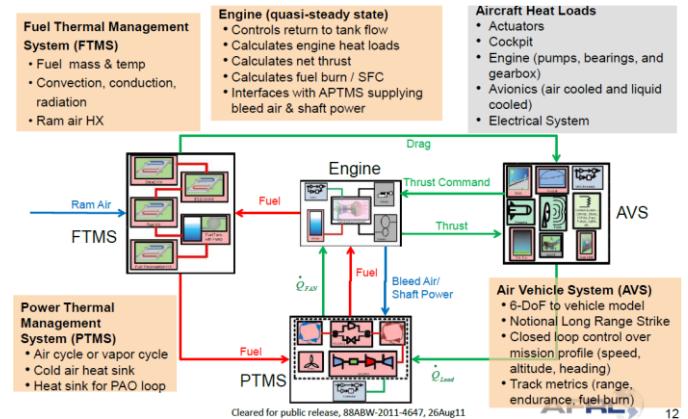


Figure 4: Thermal management system. Tip to Tail model (mission level)

The interaction between the aircraft power systems, the mission and its flexibility, the true physical environmental constraint and the standardized artificial environmental constraint contributes to constitute a field of potential improvement at aircraft level: Design methodologies, models and tools for optimal system design will therefore play the key strategic role and we will try to highlight the gap in this paper in the perimeter of electrical engineering.

## C Current lack of methodology maturity

The complexity of aircraft power system optimal design is high, maturity of integrated design by optimization methodology for such a complex system is currently too low to be used in the early phase of next programs [55], [2].

Defining tools, models and methodology to support electrical system design by optimization still requires a large collective work, independent of private interest to maintain legacy solutions.

## D Content of the paper

Our objective hereafter is to open the dialogue on top level design methodology aspects, review the main requirements for a design framework and discuss a joint plan between academia and industry for the development of next design methodologies for future electrical systems.

In the following, we will highlight the potential interest of developing so called design by optimization methodologies in an integrated way, and describe the basics of such a methodology including the properties of a suitable tool.

Then we will review through some examples the current penetration of design by optimization methodology in the public design space.

## **II. Brief review of electrical engineering design methodologies by optimization**

### ***A History and current advances of design by optimization approach***

In order to clarify the following, we define “inverse problem” (the design problem) for the electrical system how to synthesize the best architecture, system and component dimensioning, and power management for a given mission and environment. For an electrical machine, the inverse problem is which structure to choose, what dimensioning and design parameters. On the other hand, the direct problem consists in defining the performances of the chosen design, and in finding the performances of this structure and design parameters.

An historical review of electrical system design methodology will outline that, due to the increase of computing capability, finite element tools were at one point considered as the future and that it will make obsolete any analytical method using equivalent schematic surrogate models and associated assumptions from the whole design chain for both the direct and the inverse problem. For the direct problem, the continuous increase of simulation capabilities was showing that the direct problem with FE tools will be solved much more accurately than with manual analytical calculation and abacus even automated. However, in the opinion of the author, FE approaches are only available on the final step of the design of some device, e.g. to refine few performances on some local critical performances acting on few parameters. For example, this deals with the saturation around the slot of an electrical machine. Such an approach cannot be applied for the design with numerous parameters and constrained, at the system level approach used in the paper. This is discussed in the next sections.

Today there is a mix of analytical and numerical software tools to solve the direct problem, analytical being very much faster and less accurate (but keeping the parameter sensibilities). For the inverse problem, similarly to the direct problem design, software tools have been developed for both requirements capture and design synthesis through specific programs executing dimensioning procedure for a given structure.

Enabled by fast and huge progress in information technology, the models and knowledge to solve the inverse problem and to study physical behavior for the direct problem have diverged in specialized directions due to two new approaches.

One method is optimization under constraints of a given objective function, another one is the use of artificial intelligence: Expert systems using inference engine research for electrical system design optimization were almost abandoned during the 90's and are regaining interest now as we will show later on[55].

In mathematics and computer science, an optimization problem is the problem of finding the best solution among all feasible solutions. The formal mathematical model of a mono-objective optimization problem is a statement of the form: *minimize*  $f(x)$  subject to  $h_i(X) = 0$ ,  $i = 1..k$ , and  $g_j(X) < 0$ ,  $j=1..m$

where  $X = [x_1; x_2; \dots; x_n]$  belongs to  $S$ ,  $S$  represents the research space.

where  $f(X)$  is the scalar-value of objective function, to be minimized, that is function of the design variables  $X$ .

$g(X)$  and  $h(X)$  are the inequality and equality vector-valued of the constraint functions.

Optimization under design constraints for a given objective function uses an analytical parametric model that captures through mathematical equations the behavior of the object, including in fact the same knowledge that is used to solve the direct problem linking design variables and constraints to output performances.

This design by optimization method leverages of course on information technologies progress, and also on the fact there are many powerful mathematical algorithms and theorems not specific to the electrical engineering field to solve this type of problem.

This method has been introduced in the 70's for electrical machines and since then it has grown in performances and perimeter of application constantly.

This method uses now specific software tools, frameworks to implement methods and mathematical tooling independent of object knowledge to design objects and is well adapted to the first part of the design studies which represents 5% of the development cost and condition 75% of the product performances.

### ***B Capturing mission and system environment design drivers***

We need to synthesize a description of the system with pertinent constraints and objectives. Usually, there is both uncertainty of the real use domain and a large variety of possible profiles and environments.

Design has to take into account more than one “nominal” operating point but a simultaneous set of equivalent trajectory of each design drivers (the input design constraints): to build the proper design driver vector for dimensioning, part of constraints requirements have to be “integrated” along the mission.

Also the relationship with the system design versus mission and environmental constraints is bi-directional: the electrical system mission may be executed in different ways impacting its design choices; specific design choices may lead to a better mission capability which was not expected at first.

Defining the approach to capture the key performance and dimensioning drivers from mission profiles and environmental constraint is a research by itself: statistical method, sensitivity

analysis and optimization can be mobilized to synthesize those mission and environment representative design drivers.

Additionally the “environmental” constraint is a mixture of true physical environmental constraints, artificial standards and certification rules based environmental constraints and the induced constraints from the interaction with the aircraft and its systems, which constitute the electrical system environment.

Among artificial constraints, electromagnetic emissions and power quality public standard are imposing severe constraints on the design and dimensioning of the key component of the electrical system, the power converter. Significant improvement in power density and strong design simplification may be achieved with a systematic and global analysis of the best trade-off. Most of those public standards have been initially defined for technologies and architectures that are now obsolete. Those standards are mainly addressing the component and not the association of components within the system. The fact it should work is demonstrated by a combination of test, simulation and associated analysis mainly in normal operation, assuming the protection system will confine and clear a hazardous interaction.

While in some case the new standard may allow for instance weight saving on wiring, filtering and reduce complexity, it has to be demonstrated, and inversely new threat linked to a more dynamically controlled, higher voltage, higher power, more critical by the expansion of systems interaction may result in others constraints even more dimensioning

Design by optimization methodology can be used to analyze those interactions between mission, design constraints and performances within a complex environment by making the appropriate constraints variable, runs sensitivity analysis and optimization to find the optimal combination.

### **C Modeling, Optimization approaches, Robustness**

Analytical and semi-analytical models are preferred for many reasons, computation time, explicit characteristic giving insight and understanding of the relationships between models parameters, ease to build and couple multi-physical models. The disadvantage of analytical and semi-analytical models is its development time and its reduced generality in respect to FE numerical models. FE models can be used to improve or to validate a simplified analytical model. Numerical models are preferably used for validation of the dimensioning by optimization to reduce the number of real prototypes by simulation. In general Energy / Power System model breakdown is researched to use of generic standardized models for typical energy conversion, storage, and transport power chain; it includes the electrical machines transducers. Several level of modeling are necessary to cover the different system aspects, coordination between the different models for the simultaneous design is part of the optimization strategy, and of the different steps of architecture, dimensioning, management co synthesis.

In order to solve multi modal problems sometimes involving discrete variables in the architecture and management synthesis, an hybridization of both algorithms such as SQP (Sequential Quadratic Programming) - NSGA-II (Multi-objective Genetic Algorithm) may be efficient to explore parameter space

and to find rapidly the most powerful solutions. Note that the number of objective functions has to be limited, but other issues may be specified as constraints; the choice of input variables has to be in accordance with the problem to solve with all performance criteria, sufficient but limited with no redundancy to limit complexity.

The source of uncertainties is multiple either linked to environment, mission, tolerances on parameters, or to modeling errors. Specific indicators such as Taguchi's signal to noise ratio can be used to evaluate robustness of a solution in a given vicinity. To build robustness in the optimization, function objective can be replaced by robust effective function objective during the optimization process

### ***D Simultaneous design Objective and limits***

Energy conversion system design generally uses a sequential approach: first the functional analysis to build functional, "logical", and physical architectures, then dimensioning and finally energy management.

Simultaneous design of architecture, dimensioning and management in interaction with mission profile opportunities is desirable to reduce the number of iteration and have a higher probability of reaching an optimal design. One way is to use multi- system objectives multi design variables (dimensioning, management and architecture) under constraints optimization to jointly dimension a design [65].

Limits are that synthesis of the full architecture, and the synthesis of the management with very high combinatorial problem [55, 64]. Designer expertise has to simplify part of the optimization problem

### ***E Single level optimization limits [58-66]***

To enable simultaneous design by optimization, we need to use analytical or semi analytical fast models of reduced complexity such as power flow, or simplified electrical models not including detailed control loop aspects. This level of accuracy and complexity may not be sufficient: More detailed models for part of system components may have to be used in a second step to further improve the design, which can then be difficult to solve in a simultaneous optimization process.

Also, if the system complexity is too large, even using simplified models, the problem of design and optimization has to be broken in several sub-problems.

One approach then can be to synthesize a reduced but representative model per sub-problem and then to link all those models in a single optimization; this linkage, the global model construction and its final representativeness may be very complex and time consuming with potential issues of convergence for the optimization algorithms.

Simultaneous optimization of architecture, sizing and energy management may be then better solved by multilevel optimization strategies such as target cascading [58,66].



### *F Multi-level design by optimization approaches*

Classic design by optimization solves a single multi objectives multi design variables multi-constraints problem through a single optimization loop.

Multilevel design by optimization perform the optimization using multiple loops with models which may be different in accuracy, complexity, and computation speed and which may belong to various fields of expertise (MDO: Multi-Disciplinary Optimization)

The first main use of multi-level approaches can be to correct a very simple surrogate model, for example by using the response of the correspondent FE model. Several methods exist: one method is to build an improved model prior to optimization. The model building makes uses of response surface methodology or other mathematical methods of approximation: Diffuse Element, Kriging, Artificial neural networks, Radial Basis functions network, efficient global optimization have been used in electrical engineering.

Another type of method is Space Mapping [58,65]; optimization is carried out using a simple model: every 10 optimizations typically, the results are compared to the fine model for alignment. The alignment process itself is performed through an iterative optimization process which minimizes the gaps between the two models, the so called “parameter extraction.” Several kind of Space Mapping are available, among which ASM, AM, MM.

Another important case where to use multilevel strategies is where there is the need to break down a very large optimization problem; again there are several methods to achieve this target:

- one is to assemble simplified models for each subsystem to build a new one for the overall system.
- Another one well suited to complex problem is Target cascaded optimization: it maintains the hierarchic breakdown and manages the interaction between the various sub problems during the optimization. Each sub problem can use its own algorithm. Objectives are set for each optimization sub process and all associated responses are propagated to each sub system until the sublevel target has become identical. The local optimization for each subsystem tries to zero the gap between the local optimal result and the download upper level objective.

### ***G Design framework critical characteristics***

Environment tools like Matlab /Simulink, Cadence, Amesim, Saber, Simplorer, Pspice, Portunus, Flux D/3D are environments which have poor interoperability. Therefore, environment type tool are not suitable to solve efficiently multi-physical multilevel model optimization problems, which requires indeed a strong interoperability with all major commercial environment tool such as listed above.

In addition, the capability to be executed in a distributed approach is nowadays essential for a design collaborative platform, environment tool are limited to execution on a single computer.

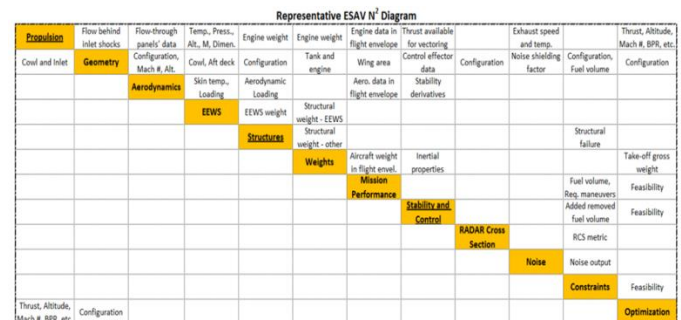
However, each component of the optimization model can be very efficiently optimized using gradient approaches allowing deployment of efficient multilevel optimization strategy on large systems (e.g. sequential quadratic programming: SQP).

In this way, one key of a design framework for optimization is the generation in an automated way of all the derivatives for a majority of models input description types by including in the framework all mathematical computation capabilities required to support the computation of that derivatives

Use of hybrid optimization Genetic algorithm (GA) + SQP algorithm further increases the framework capability to enables efficient hierarchical optimization of large system, which model component may include discrete variables

The framework is made of software component building blocks, designed for the standards that guarantee interoperability with other modeling and calculation “environment” type tools, offering plug in plug out capability for other applications in addition to its own applications.

An example of multi-disciplinary optimization framework at aircraft level is shown in figure 5 [51].

Figure 5: Example ESA N<sup>2</sup> diagram [51]

### ***H Summary of the design by optimization methodology opportunity for the aircraft electrical power system [40],[41],[55-65]***

There are strong links between the type of optimization problem, the type of input variables, the mathematical characteristics of the model to be optimized, the algorithms choice and sequence strategy.

There are strong links between the structure of the model to be optimized (multilevel), the coordination strategy between the various parts of the model to be optimized, the method to build and enrich the initial surrogate model to build the model to be optimized.

The importance of the tool is shown by the above; it has to enable adaptation of design optimization problem capture to the particular case, to support large multilevel model hierarchies. Its mathematical capabilities allied to its enhanced interoperability through plugin-plugout smart interfaces for model capture or export, will free the designer to concentrate on the design problem formulation where there is very large creativity space and to enhance both the description of the optimization problem and the structure of the model.

All methods to enrich a surrogate model using FE, are very interesting because it will further enable larger use of the methodology design by optimization. To solve “simultaneously” the design triptych dimensioning, architecture and management in the perimeter of optimization that extend soundly the search space, new research on both methodologies, tools, frameworks have to be conducted including for instance expert system inference engine methods.

For more explanations and insight in the above discussion on design by optimization methodologies, one can refer to [29-34], [40], [41], [55-61].

We will now make a core sample within available public data to sense maturity of design by optimization methodology starting at converter, sub system level and finishing at system level.

### III. A core sample of integrated design by optimization methodology from recent studies

#### A Converters, Machines and Subsystem level

Design of a power electronics converter consists in topology selection, controls, power stages heat sinking and passives: See figure 6 approach proposed by Bo Wen et al [9] for a simplified view of converter design process. More complex similar view exist [35-40]. Many computer aided design tools are available typically numeric simulator circuit's types or FE for each different field to solve the direct problem. Fewer tools are dedicated to converter, machine design synthesis through inverse model optimization especially in the early phases of design where 75% of the cost and the performance is set. The design process using iterative simulation of the direct model is tedious and do not ensure optimal design.

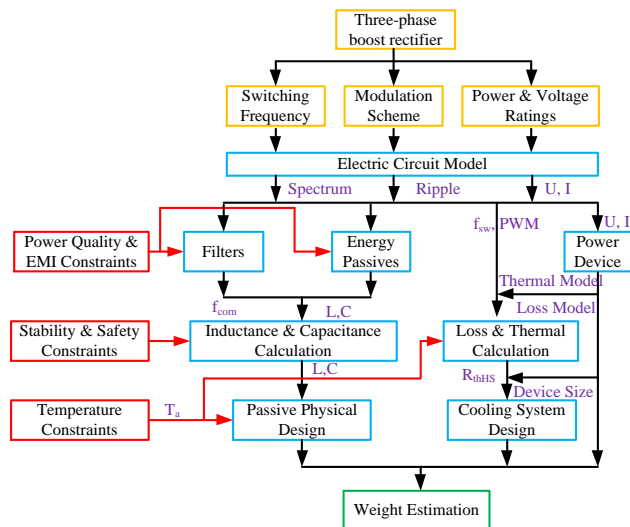


Figure 6: inverse problem illustration for weight estimation

An alternative to this simulation traditional approach is to solve the inverse problem through multi-objective multi constraints optimization, in which the objectives are for example to minimize the total converter mass and power losses.

To solve the inverse problem, technological equations need to be synthesized to express relationships between design variables, design constraints and objective functions: those technological equations are the “inverse model” and they capture, through various modeling approaches, the physical fields involved in a converter system, from magnetic to electrical, thermal and mechanical.

This trend to design converter and machine through optimization using the inverse model is not new and it is more and more used for electrical systems and many others field. We give hereafter examples of this trend for converters and machines

Busquets-Monge et al in reference [3] (2001), describes an automated design optimization approach of a 1.15 kW boost power factor correction (PFC) circuit to optimize the converter cost using a gradient based algorithm. Then in reference [13] (2002) they presents an approach to optimize a boost power factor correction (PFC) with the objective to minimize the total component cost using Generic Alorithms and a component cost data base [18]. The design constraints are the converter specifications, such as operating power and voltage ranges, EMI standards, size, and lifetime, as well as the component safe operating areas. The design variables are the switching frequency and the selection of the actual, commercially available components and materials. The GA provides for a systematic and efficient search of the databases of preferred components, which contain all (datasheet-based) component parameters that are necessary for evaluating the constraints and objective function.

S. Chandrasekaran et al in [19] (2002) analyse the weight minimization of a buck converter and its input filter. Network stability criteria are part of the optimization constraints. The global optimization (converter +filter) leads to a lower weight than the two separated optimization.

Also Drofenik et al in [7] (2005) described a design procedure of design forced air cooling system. Converter power density limits for forced convection cooling is analyzed.

Kolar et al in [8] (2007) investigated the volume of cooling system and main passive components for the basic forms of power electronics energy conversion if function of switching frequency.

Rivas-Avalos et al in [34] (2007) make a survey to value interest of evolutionary algorithm for multi-objectives optimization.

I. Kovacevic et al in [35] (2008) analyse the weight optimization of wearable power system comprising of an IC engine, motor/generator, inverter/rectifier, Li-battery pack, DC/DC converters, and controller for a given mission: SQP and SUMT algorithm performances are compared.

Rixin Lai et al in [4] (2008) introduced a systematic methodology of topology evaluation.

Guichon et al in [17] (2008) analyse the impact of the design of the output filter of a three phases inverter on both total converter losses and cost through optimization: the optimization process is as shown in figure 7.

The design constraints are all physical limits of filter material and components, the output voltage waveform THD, max output inductor voltage, load short circuit capability. The design variables are the topology and its control law, the switching frequency, inductor design parameters (number of turns and magnetic circuit) and capacitor values and are simultaneously selected to find optimal combinations. Continuous model are synthesized to compute the derivative and use an SQP algorithm which allows handling a large number of variables and constraints while finding optima in typically less than a one minute. Pareto curve are defined for several magnetic material. Optimization results show the wideness of potential optimized solution and the interest of the methodology to first find the optimal couples, to orient the design choices in a very efficient way not achievable with direct design based on iterative simulation.

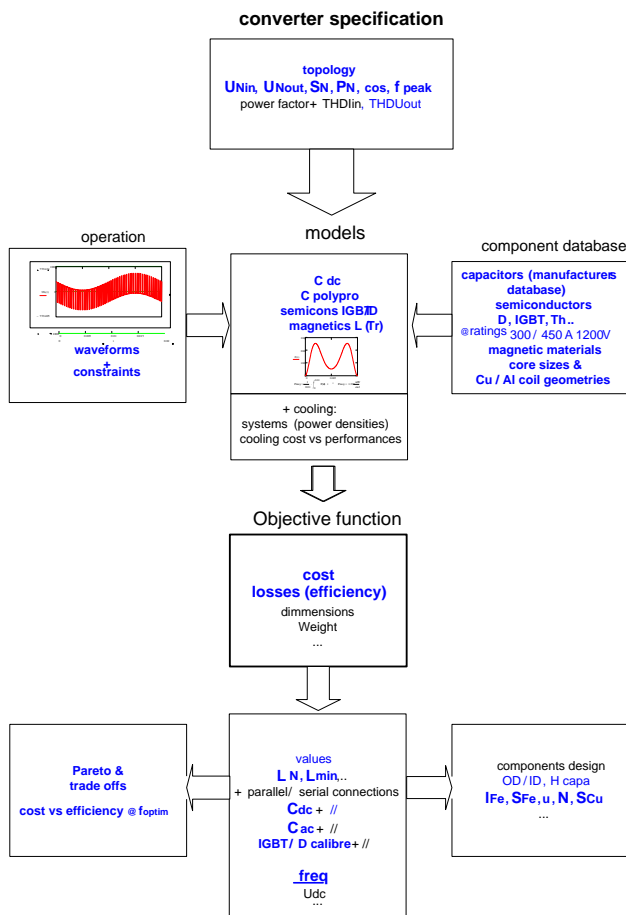


Figure 7: converter losses vs cost optimization

Raggl et al in [36] (2009) analyse the design of a single-phase boost power-factor correction (PFC) circuit and its optimization.

Biela et al in [37] (2009) propose a procedure to choose modularity, operating point, and silicon area for interleaved paralleled DC-DC converter to optimize system efficiency

Waffler et al in [38] explore the limits through multi-objectives optimization of power density as a function of the switching

frequency and the number of phases of non-isolated bi-directional multi-phase dc-dc converters operated with soft-switching and Silicon devices and hard-switched converters that take advantage of SiC devices.

R.Wang et al in [6] (2010) analyze the required energy storage capacitor based on minimum ripple energy.

Heldwein et al in [7] (2009) estimate the impact of electromagnetic compatibility (EMC) filter on the power density.

S.Wang in [10] (2010) formulate the design of dc-dc power converters as a multi-objective optimization problem to minimize the total converter mass and power loss. GA-based optimization is used to define the Pareto optimal solutions at the converter module level, and for the main components. To boost optimization process, pertinent computationally efficient and accurate component models are synthesized using GA based design search and curve fitting techniques.

Friedli and Kolar in [5] (2010) compare three-phase ac-ac matrix converter and voltage dc-link back-to-back converter topologies through detailed technological dimensioning equations

Biela et al in [39] 2010 propose analytical models for losses of a PFC rectifier with integrated magnetic; an optimization of the converter for minimal losses is performed and the sensitivity of the efficiency on the switching frequency and the operation mode is analyzed.

Kolar et al in [40] (2010) analyse the interest of using design by optimization methodologies to study competitiveness of a given set of technologies for a given system and mission: parameters defining variability of converters system structure by converters association are potential variable of the multi objectives performances optimization. System power normalized performances is characterized by output power density  $\rho$ , output power weight density  $\gamma$ , efficiency  $\eta$ , failure rate  $\lambda$  and \$/KW  $\sigma$  as main performance indices. System Pareto front hyper surfaces between the performances indices can be used to find the technology nodes ( $\rho, \eta, \sigma, f_s$ ): finding switching frequency that minimize cost/kw on the Pareto hyper surface defines a technology node ( $\rho, \eta, \sigma, f_s$ ); design by optimization methodology can be used for road mapping by analysis of the performances improvement associated to new technologies improvements through Pareto curves of different potential structures. The multi objectives multi-constraint multi variable optimization frame-work allows, by technological constraints sensitivity analysis, to define the system improvement achievable by improvement of the technology.

Bo Wen et al in [9] (2011) develop relations between efficiency, power density and switching frequency for a three-phase two-level PWM boost rectifier to estimate its weight.

Toure et al in [20] (2011) propose an EMC equivalent circuit using high frequency models for each part of the system [21-28] (electrical components, cables, machine...): the inverter switches are replaced by equivalent sources as shown in figure 8. All LC parasitics are identified as shown in figure 9; hence, from the associated net list file, the frequency model is automatically generated as an ICAr software component



including the gradients related to the model inputs [29-33]. The design variables are the cable characteristics, the filter corner frequencies and associated filter LC values and geometrical data. The design constraints are the D0160 requirements, the control strategy, the switching characteristics, the magnetics and thermal limits of filter components, the inverter model (semiconductors, layout, etc.) values, the AC machine model values; the objective function is to minimize the output filter size.

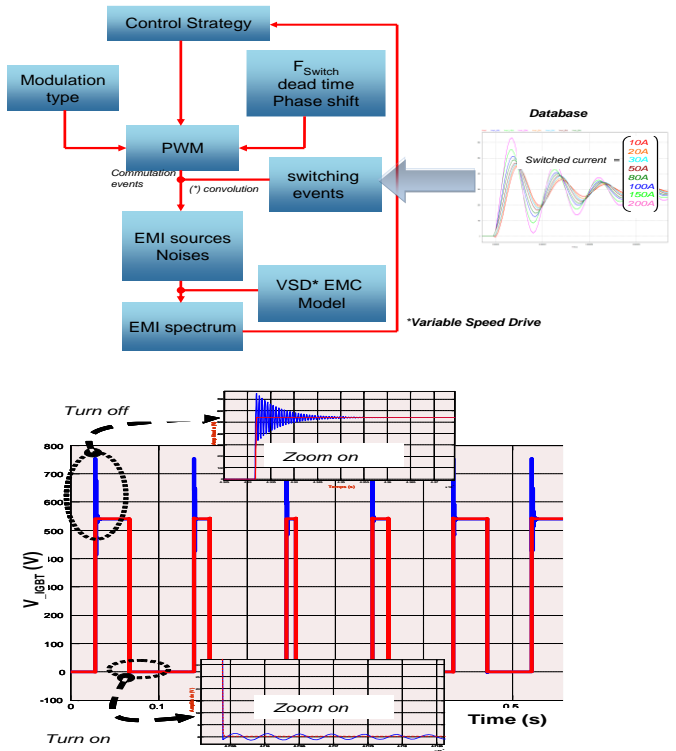


Figure 8. Elaboration of EMI noise sources. Top: principle – Bottom: illustration in the time domain (ideal voltage -red and reconstituted voltage -blue).

Trentin et al in [14] (2012) propose a novel method to design the input filter, including its topology, for a direct ac/ac matrix converter: A Genetic Algorithm (GA) is used to optimize structure and parameters of the input filter as a function of different factors such as energy storage, weight, and volume while meeting power quality constraints through a fitness function. This design method is then evaluated through a wide range of simulations using Saber and experimental results on a laboratory prototype

Okaeme and Zanchetta in [16] (2013) propose an hybrid bacterial foraging (HBF) algorithm combining global search capability of the GA and the local search potential of the bacterial foraging (BF) algorithms. This solution is then used to optimize the structures and the parameters of digital speed controllers experimentally and directly on the drive while it is subject to different types of mechanical load.

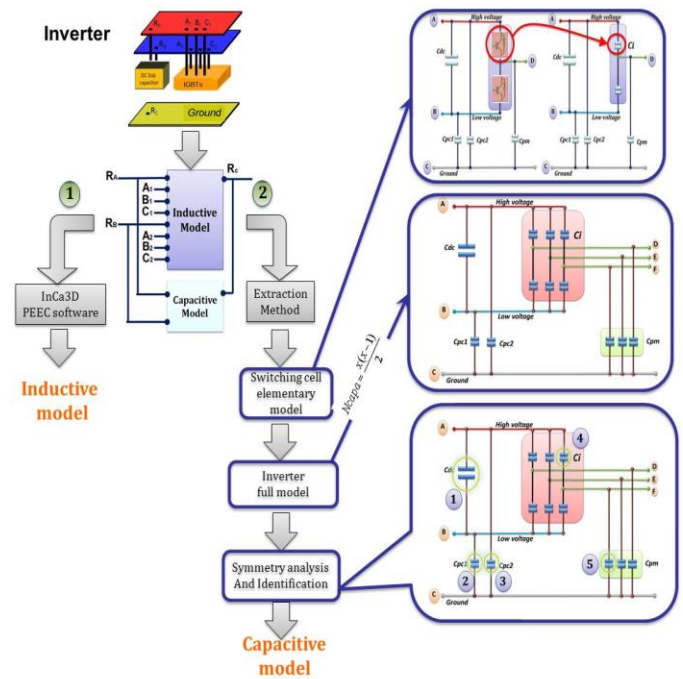


Figure 9: Methodology of the converter and its components multi-objective optimisation

Gerada et al in [15] (2014) propose an integrated design weight optimization methodology for an helicopter EMA. The main non-linearities in the electrical machine reducing the torque constant are taken into account through a “dynamic” reluctance network; thermals aspects are modeled through a resistances network. Particle Swarm Optimization (PSO) is used to optimize the system weight.

Roboam et al in [53] analyse the technological and architectural trends of the more electrical airplane and describes interest of using an integrated design by optimization approach: “it consists of coupling dimensioning models with an optimization algorithm to optimize system criteria (weight , losses, etc) while satisfying technological and operational constraints (thermal, power quality, stability, emc)”. Authors give two examples of such optimization at subsystem level; one is a power channel as shown in figure 10 [59] [63]. The power channel is optimized for total weight and losses tradeoff, integrating the generator, diode rectifier and filter interactions. Harmonics level requirement is challenged through optimization. Another example is an ECS subsystem consisting of an electrically motorized compressor. The ECS subsystem multi-field modeling is shown in figure 11. This typical problem involves 21 design variables with 2 of discrete type, 20 constraints and 2 objectives. Flight sequences are integrated in the system optimization.

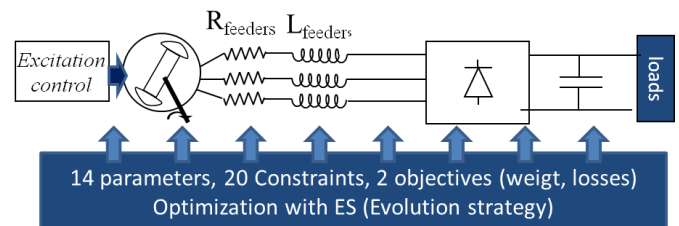


Figure 10: optimization of a HVDC power channel integrating WR synchronous generator with six pulses rectifier and filters

## B System level

Multi-disciplinary optimization methodology has been used in many fields, including early conceptual aircraft design, for many years and it is boosted by information technology progress from manual spreadsheet to distributed design framework.

We can find examples of such early concept studies at Aircraft level or at system level for some systems such as flight control actuation : Allison et al in [51] (2012) presents a modular multidisciplinary analysis and optimization framework tool built to optimally designing a supersonic aircraft

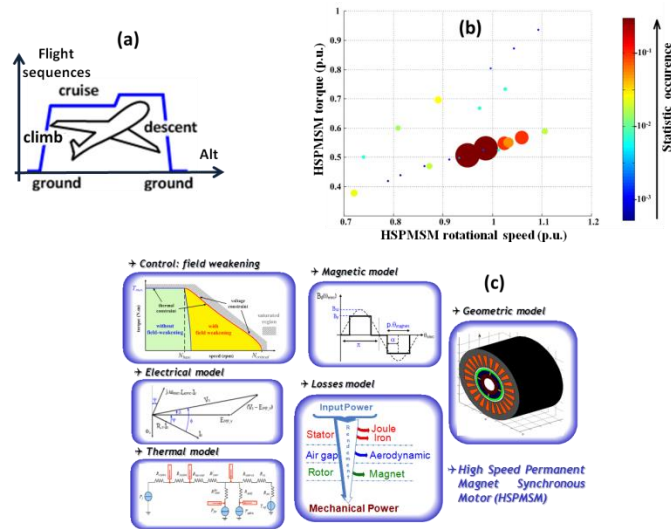


Figure 11: Multi-field modeling of inverter fed HSPMSM actuation system for the ECS

Bauer et al in [50] (2007) describe a flight-control architecture weight optimization process: To reduce the initial combinatorial complexity and surface possible architectures, a subset of the search domain is built taking into account technological constraints and in-house design rules. Then a branch-and-bound search algorithm is used to solve the remaining discrete optimization problem.

Haitao et al in [52] propose to optimize the weight of the flight actuation system through use of GA.

Traditionally the electrical system design does not use a MDO framework solving the inverse problem for component sizing, architecture sizing and management choice. Initial trade studies between potential architectures are achieved through a mix of expert review of potential architectures adapted from previous similar aircraft, in house design rules. Potential improvements of new technologies are evaluated in delta performances at a subsystem level; spreadsheet load analysis of mission points methods and other design standards permit to size the power rating of components and associated weight, volume and losses. Simulation using the direct model then allows to verify some aspects of the power quality and stability, and EMC can be evaluated after the preliminary design phase. Until recent times, inverse model MDO approach was not used for the

electrical system design. It corresponds to the Preliminary design phase of the development process of an aircraft as shown in figure 12 [2].

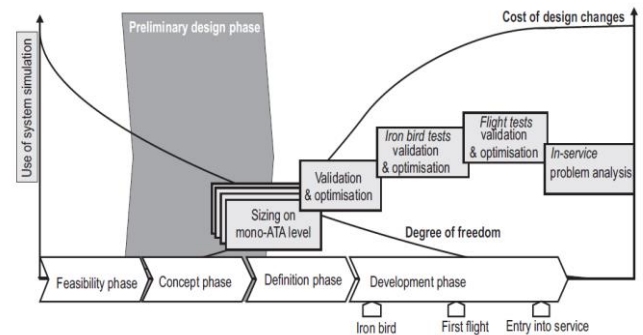


Figure 12: Aircraft design phase state of the art M&S reference

The JSF MADMEL, the Sonic Cruiser advanced studies, the launch of the Dreamliner and then the replacement of Short Range CA, have triggered an intense R&D activity around the concept of more electrical airplane. The resulting R&D effort from 2000 to 2010 has been first focused at improvement of technologies at component level, improving modeling and temporal simulation of equipment to validate design and integration.

One example of assessing power systems performance at aircraft level by simulation is described in [54] (2008) Kuhn and Al describe the classic steady state, average and switching models and their domain of use to analyze. Power quality and Stability are discussed together with the implementation in a multilevel software component approach, as well as the path to other tools such as Modelica/Dimola environment.

Liscouet et al describe in [2] (2008) the creation of a simulation "framework" in a Matlab & Simulink environment using Modelica, a white box to compare architecture performance per simulation. A generic multi energy power system module defined as an object oriented building block is proposed to model all main power conversion functions of the aircraft. The model includes the relationships between input power, output power, a set of aircraft level input and system level inputs; the module computes weight, drag using simple algebraic equations. The methods uses a two steps process. First, weight and drag are obtained using "inverse" simulation depending on the output power. Another simulation sizes then the components, using this result, and estimate the system performance at aircraft level as shown in figure 13 [2].

Recently, a breakthrough in analysis of electrical power system design methodology was proposed in " Methods and tools towards optimal design of aircraft electrical network" [55,64], Giraud investigates optimization of the load allocation at aircraft level using graph modeling and knowledge based classification methodologies to optimize the load allocation to bus bar and the source to bus bar allocation to minimize the installed weight due to load combination power flow (feeder, generator, power center dimensioning).

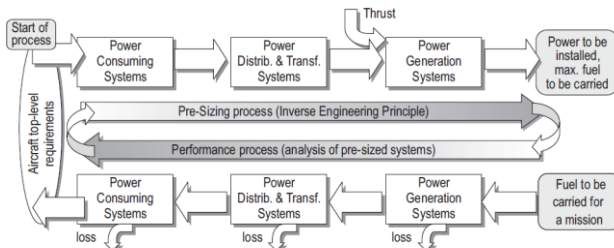


Figure 13: Inverse problem to define power need (Liscouet 2008) through surrogate power flow models

This study shows that the network management part (typically contactor logics) has to be optimized by models and algorithms or knowledge rules different from those used for continuous system like for machine or converter dimensioning. It uses "classification methodology" for the numerous possible theoretical combinations of contactors: the "simultaneous processing" between architecture, dimensioning and management is difficult if not impossible to implement. Stated problem needs to be simplified by designer expertise to reduce the search space (reducing complexity as a goal, integrating life cycle constraint early in the optimization process, making initial choices to be tested and benchmarked through iterative explorations).

The proposed modeling approach use graph method and artificial intelligence (expert systems) to establish all potential reconfigurations, and to eliminate the ones which do not respect some technology rules (like connecting DC on AC) or expert rules (example to not parallelize two sources on the same bus bar). The size of the combinatorial problem can be reduced through business and safety rules, the modeling approach is innovative.

In the same breakthrough innovative methodology dissertation, the optimization of a modular power center as shown in figure 14 is achieved through a design framework as shown in figure 15. This system combines the two types of optimization problem: high combinatorial possible choices of reconfiguration cases and multi-physics system dimensioning.

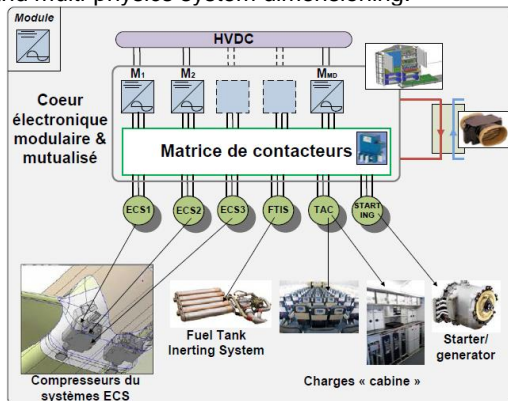


Figure 14 Power center with VSI modular resource

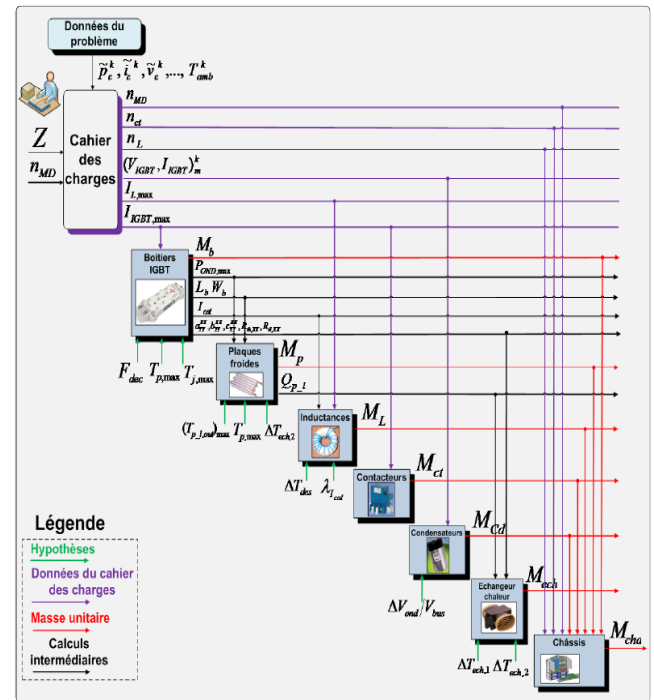


Figure 15 power center dimensioning optimisation framework

## IV. Analysis and consequences

### A Criticality of the design problem formulation

Design by Optimization is a general methodology applicable to any field for which design synthesis can be modeled mathematically. For a given formulated optimization problem with the appropriate mathematical tool, the search algorithm will find the best solution in the specified search space: This does not guarantee the optimality of the solution if the problem is not formulated correctly, or if the model is deficient to capture with enough accuracy all relevant aspects. The designer may be satisfied by the best case of a poor description of the problem or by local optima well below what could be achieved with a larger design space, and a better search strategy.

### B Requirement for a hybrid method mixing artificial intelligence and gradient based methodology

Several optimization approaches are complementary, hybridizing them in a multilevel hierarchical approach is a potential way to solve the "simultaneous "design triptych as system to optimize are complex and of hybrid nature. For instance for continuous problem, the SQP algorithm is coupled with GA to avoid being stuck on a local optimum. Figure 16 show a typology of optimization case and associated algorithms FOM (figure 17). For large combinatorial problem typical of the management of the electrical power system, knowledge based systems methodology implementing designers rules with specific graph theory algorithms can help the optimization process.[55], [64].



### C Requirement for a power systems MDO framework including a propulsion and aircraft structure surrogate model

The optimal electrical system has strong links with the optimal electrified thermal management system and with the other electrified systems. A surrogate model of both engine and aircraft structure shall enable to perform optimization of the entire power system towards its mission .The important links between power systems, engine and aircraft structure are shown in figure 3.

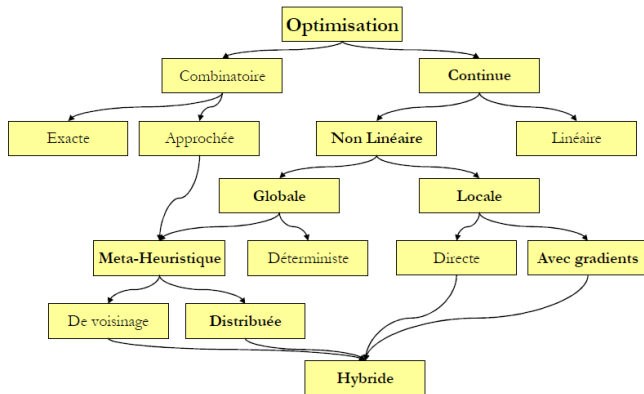


Figure 16 typology of algorithms

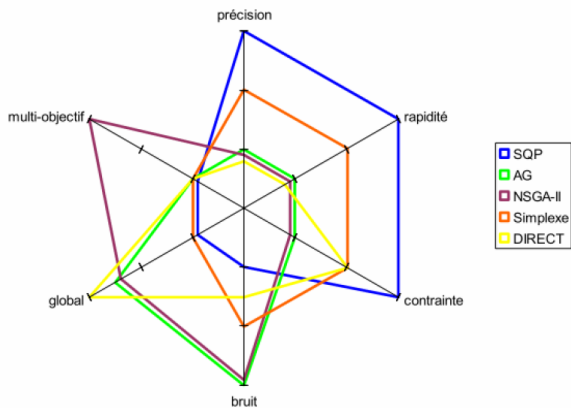


Figure 17: Algorithms Figure of Merit

### D A challenging task

To achieve such MDO optimization is a challenging task which requires progress on tools, models and methodology.

Designer expertise is necessary to define a sound formulation and to simplify for instance too large combinatorial problem.

Artificial intelligence methodologies, Expert system approaches, Bond graph theory, Statistical methods to classify and concatenate requirements, Hybridization of search algorithm, Space mapping techniques, Response surface methodology, Approximation techniques such as Diffuse Element, Kriging, Artificial neuron network, Radial Basis functions network and strong mathematical tools to extract derivative properties need to be harmonized.

The associated framework shall be greatly interoperable, open, support white and black box and ball models and geographically distributed co-optimization co-simulation as shown in figure 18.

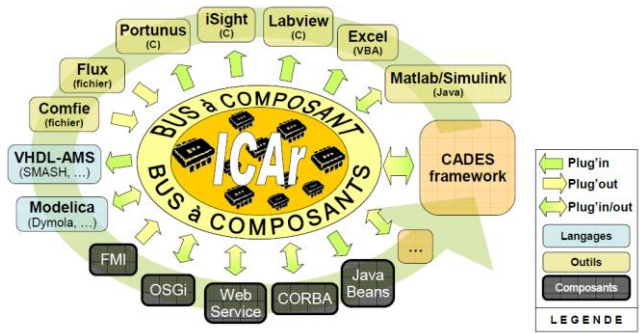


Figure 18 Modular interoperable framework

Also this research has to make use of the relevant technology metrics for upcoming technology roadmap to synthesize the right architectures and level of control. The technology roadmap formulation methodology using the technology node approach given by Kolar in [40] will permit sound technology selection and support to reach the productive phase.

### E A collective effort proposal

Therefore an initiative of a joint research consortium project has to be launched to raise TRL level of methodology to optimize the aircraft energy conversion system including electrical and heat energy and the other "supplied systems". Methodology shall be understood from initial problem formulation, simplification up to capability to co-design in a geographically distributed multidisciplinary framework such as shown in figure 19 [62]

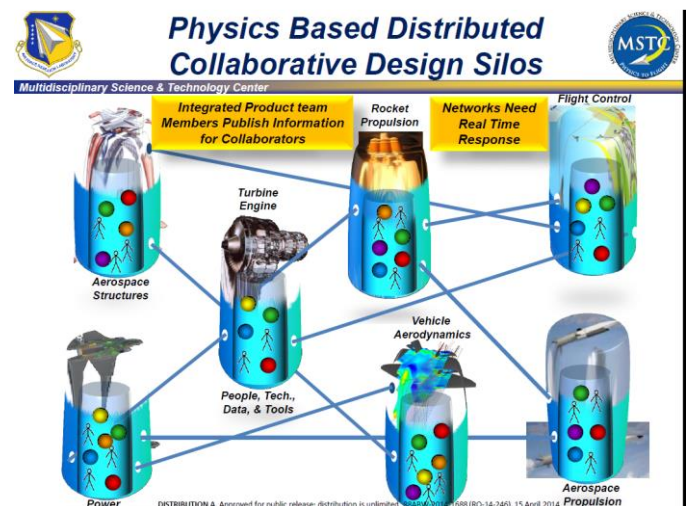


Figure 19 Optimus MDO framework vision

This research consortium is an industry academia public foundation consortium type.

The case chosen to illustrate the methodology is the next short range commercial aircraft.

Industry, government, industry sponsors and technological partners will benefit of impact of the research to increase west countries aerospace industry competitiveness in that field of energy conversion system for next SRCA.

The academia research centers that are supporting this initiative are: Center of electrical Power systems (CPES) at Virginia tech, University of Nottingham Power Electronics, Machines and Control Group; Université de Toulouse, LAPLACE laboratory,; G2ELAB Université de Grenoble. Those academia research groups are currently the leading ones in the field of aerospace power systems. Other academia and technology partners will join in particular for thermodynamic systems modeling..

## V. Conclusion

In sketching the challenges of next SRCA for the electrical system and thermal management systems we have reviewed the so called integrated design by optimization methodology, models and tools to conduct MDO study of a joint power and thermal systems.

We also extract core samples form published studies on design and optimization of aircraft systems with a focus on power converters, to build an indicator of optimization methodology maturity for large hybrid energy conversion systems such as next SRCA. We finally have introduced a research initiative to raise that maturity. This initiative has already received the support of Air Force Research Laboratory in the frame of the Optimus program [62]. The way-forward will consist in several workshop to further explain the project, define more detailed roadmap and build the opportunities network.

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