Some meta-modeling and optimization techniques for helicopter pre-sizing

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Abstract

Optimization and meta-models are key elements of modern engineering techniques. The Multidisciplinary Design Optimization (MDO) allows solving strongly coupled physical problems aiming at the global system optimization. For these multidisciplinary optimizations, meta-models can be required as surrogates for complex and high computational cost codes. Meta-modeling is also used for catching general trends and underlying relationships between parameters within a database. The application of these mathematical techniques to the pre-design of rotorcraft is well relevant. Indeed rotorcraft pre-sizing is a multidisciplinary issue involving flight dynamics, aerodynamics, power generation, structures, … Moreover the rotorcraft databases requires meta-modeling techniques to be useful. This paper presents several techniques studied by ONERA in the C.R.E.A.T.I.O.N. project. The practical case considered here deals with the helicopter main rotor optimization.

NOTATION

Mission point parameters:

Vh, Vz,	Horizontal and vertical rotorcraft speed (m/s)
ρ, g	Air density (kg/m^3), gravity constant (m/s^2)
T0, P0	Standard absolute temperature (°C) and pressure (Pa)
Zp	Altitude pressure (m)
SAR	Search and rescue mission
Cson	Speed of sound (340 m/s)

Rotorcraft main parameters:

Wmto	Maximum take-off weight (kg)
Wempty	Empty weight (kg)
Preq	Total required power
Paf	Airframe drag power (kW)
Laf, Haf, Waf	Respectively length, height and width of airframe (m)
Vmax	Maximal cruise speed (m/s)
Vbr	Best range speed (m/s)
Vbe, Vy	Best endurance speed (m/s)
Vroc	Best rate of climb speed (m/s)

Main Rotor parameters:

R	Main rotor radius (m)
c	Blade mean chord (m)
b	Number of blades
Sblades	Blade surface (R.c.b) (m^2)
Nr	Rotation ratio (rpm)
Ω	$\Omega = 2.\pi/60.Nr$ (1/s)
Vtip	Blade tip speed (m/s)
σ	Main rotor solidity
µ	Advance ratio (Vh /Nr.R)
Cxp	Blade mean drag coefficient
Czm	Blade mean lift coefficient
kmr	Correction factor for induced power
T	Main rotor thrust (N)
Pind	Induced power (kW)
Pblade	Blade drag power (kW)
PreqMR	Main Rotor required power (kW)
Vi0	Froude rotor induced velocity in hover (m/s)
Vim	Mean induced velocity (m/s)
η_s	Performance index for hover
L/De	Performance index for cruise

Engine parameters:

Pto	Take-off power delivered by all engines (kW)
Pmc	Maximum Continuous power delivered by all engines (kW)
Dm	Fuel rate of consumption (kg/s)

Miscellaneous

MDO	Multidisciplinary design optimization
AAO	All at once

1. INTRODUCTION

After introducing the CREATION project which is the framework of this study, the models used in this paper will be presented in section 2. Then a brief background on MDO approaches will be given in section 3. In section 4, we explain the main rotor optimization. In section 5, we present the MDO applications. Finally we conclude and present our present of the MDO optimization in the CREATION project.

1.1. The CREATION project

This federative multi-departments research project has been launched by ONERA in January 2011. C.R.E.A.T.I.O.N. stands for “Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network”. The first steps and the foundations have been presented in [1]-[2]. The main goal is the development of a multidisciplinary computational platform for the evaluation of rotorcraft concepts. It concerns both flight performances and environmental impacts as acoustics, fuel consumption…

The CREATION platform is based on a multidisciplinary and multi-level modeling approach. The multi modeling levels are defined to allow the evaluation of any rotorcraft concept whatever the level of details in the description data. It includes cases with very few available data, for instance, if there is only an idea of new concept. Therefore the tool must be able to cope with the preliminary conception and pre-sizing problems.

The multidisciplinary feature comes from the rotorcraft nature itself. Thus the tool is composed of the chaining of seven computational modules:

- Flight Mechanics,
- Aerodynamics,
- Power Generation,
- Acoustics,
- Weights and Structures,
- Architecture and Geometry,
- Missions and specifications.

The lowest level of the models (i.e. the most simple one) implemented in these modules is described in the part 2.1.

1.2. Application framework

The first year of the CREATION project aimed at developing the modules with different levels of modeling for the practical case of an existing helicopter: the SA 365N “Dauphin” (Fig 1). These developments have been presented in [2].

The second milestone of CREATION deals with the pre-sizing capability. Therefore optimization techniques must be investigated taking into account the multidisciplinary feature of the pre-sizing problem. Thus the multidisciplinary design optimization (MDO) framework is well adapted to the CREATION studies. Various MDO schemes are possible such as: All at Once, Collaborative Optimization, etc. the section 3 will briefly describe this field of optimization techniques and the use of the All at Once approach.

The context of multi-mission requirements is particularly interesting because it implies some design trade-offs that MDO can investigate. Among others offshore and search and rescue (SAR) missions present “divergent” interests. Offshore mission requires good performances in cruise flight conditions while SAR imposes good performances in hover and low speeds. Both missions are considered in this study.

Offshore and SAR are in the range of missions of the SA 365N Dauphin helicopter. This rotorcraft is a good candidate for our optimization exercise. In continuity with the first year of the CREATION project, it provides a well known comparative basis. The main rotor is the most important part of a helicopter ensuring both lifting and propulsive functions; it has a crucial impact on the flight performances. In this paper, the focus of the investigation concerns the optimization of Dauphin’s main rotor while the rest of the helicopter is unchanged. The main Dauphin performances and characteristics are summarized in Table 1.

	SA 365N
Dimensions Laf x Haf x Waf	11.44 x 4.01 x 2.03 m
b	4
R	5.965 m
c	0.405 m
Nr	350 rpm
Wmto	4000 kg
Arriel 1C Pto	492 kW
Arriel 1C Pmc	437 kW
Vmax	292 km/h
Vbe	140 km/h
Max range at 260 km/h	937 km
Max endurance at 140 km/h	4,4 hr
Hover ceiling OGE at take off power – ISA	600 m

Table 1: SA 365N performances and parameters.

Fig 1: image of SA 365N from CEV of Istres.

2. MODELING BASIS

2.1. Modeling at level 0

As already mentioned each disciplinary module in the CREATION platform contains different models corresponding to different levels of details in the description of the rotorcraft. At the lowest level, the models are simple and fast. Very few input data must produce the essential of main flight performances and environmental impact. The models at this first level are analytical based on first principles and / or extracted by meta-modeling techniques from databases. Inputs and outputs are summarized in the tables following the description of these first level models in each module.

Flight performances: Balance of Power (BP) also called energy method is an analytical model based on the balance of the main forces. It calculates the required power P_{req} to flight in stabilized conditions. The number of inputs is reasonably low and the precision of results is satisfying. This method is limited because it lacks rotorcraft moments hence not taking into account rotorcraft attitude angles.

Flight performances
Inputs: Geometry module: b, c, Nr, R Aerodynamics module: Cxp, kmr, CxS Mission module: Vh, Vz, ρ, g Weight & Structure module: Wmto
Outputs: Preq, T

Aerodynamics module: This module evaluates the aerodynamic characteristics. At first level, it uses simple analytical formulae to calculate the induced power correction factor Kmr [1, 3], the mean blade drag coefficient of main rotor $Cxp = f(\mu, Czm)$ and the airframe drag coefficient CxS_{af}. The aerodynamic module is of course coupled with the flight performances module.

Aerodynamics
Inputs: Geometry module: b, c, Nr, R, Laf, Haf Mission module: Vh, ρ, T0 Flight Perfs module: T
Outputs: Czm, Czm$_{max}$, kmr, CxS$_{af}$, Cxp

Power Generation module: At level 0, the engine can be sized using required flight power. The model is based on an engine database and regressions. This study considers the Turbomeca Arriel 1C of the Dauphin SA 365N. The code computes available power for different flight conditions (temperature, pressure, altitude).

Power Generation
Inputs: Performance module : Preq Mission module: Vh, ρ, T0
Outputs: Pdisp, Cs

Acoustics module: The lowest level uses a dimensional analysis of the Ffowcs-Williams-Hawkings equation following the approach of Leverton [4]. The result is a ratio of global level of noise $Facou$ with respect to a reference one which is in the present case, the emitted noise by the basic SA 365N.

Acoustics
Inputs: Geometry module: b, Nr, R Weight module: Wmto
Outputs: Facou

Weights and Structures module: The first level of this module aims at evaluating the weight of the rotorcraft using statistical formula. In the present optimization case, the blade chord and radius are varied hence impacting the rotorcraft empty weight. The weights and structures module calculates the blade and hub mass with analytical equations based on mechanical constraints. This model takes into account materials characteristics (epoxy/glass fiber, etc.) and general geometrical information about hub and blades.

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Weights and Structures
Inputs: Flight Perfs module: Pto, Geometry module: Nr, b, R, c
Outputs: Wmto, Wfuel, Wrc, Wempty, Whub, Wblade

Architecture and Geometry module: This module gives information about the sizes and geometry of the rotorcraft. It can be the main rotor blade number, mean chord, rotation speed or the main dimensions of airframe… When the rotorcraft characteristics are not prescribed, this module can make use of meta-models such as regression or neural network derived from databases.

Architecture and geometry
Inputs: specifications, performances …
Outputs: R, b, c, Nr, Laf, Haf, Waf

Missions and specifications module: This module is used to specify some performances or a typical mission profile (offshore, SAR, etc.). Some specifications can be set as the initial quantity of fuel, payload or useful load weights.

Missions and specifications
Inputs: specifications, mission profile…

Outputs:
ρ, Vh, Vz, Zp, Tisa, T0, P, P0, dt, Wfuelinit, …

2.2. Validation of performances

During the first year of C.R.E.A.T.I.O.N., the models were established on each level of the rotorcraft description and evaluated in the case of the SA 365N helicopter (see [1]-[2]). Fig 2 shows an example of comparisons on the required power in level flights between the calculations and the flight test data. We can distinguish respectively in blue and green the required power calculated by the modeling level 0 (BP: balance of power) and level 2 (numerical models, HOST). The flight test points come from the RESPECT study [5].

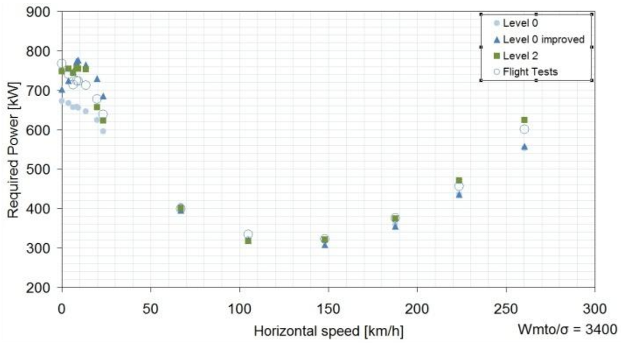

Fig 2: required power in function of advancing speed.

The differences highlight the present lacking of the level 0 models. For BP the main difference is in hover and high velocity flights. In the first case, BP does not take into account the interaction between the main rotor wake and the horizontal tail plane. Moreover it does not consider the equilibrium of rolling and pitching moments at the rotorcraft centre of gravity. De facto when the pitching attitude angle of the helicopter increases with the forward speed, the downward forces on the airframe increase which is ignored by this level 0 model. Differences from 250 km/h are explained by this and by an underestimation of airframe drag. The level 2 modeling (with HOST code option in the illustrated case) uses more comprehensive and advanced models for the rotor induced velocities (FISUW [6], MESIR [7]) as well as the aerodynamic interactions (e.g. [8]) and a complete flight mechanics equilibrium of rotorcraft (see [9] about HOST), thus the results are in better agreement with the flight data.

3. OPTIMIZATION FRAMEWORK

3.1. Multidisciplinary Design Optimization

Rotorcraft is a good example of complex systems with a lot of variables. All individual disciplines involved in rotorcraft have matured their expert models and can obtain the optimum results from their disciplinary viewpoint. However they may not yield the best result for the overall system, thus the improvement of rotorcraft requires the study of the couplings between the various disciplines (aerodynamics, structures, flight performances, acoustics, power generation). The Multidisciplinary Design Optimization (MDO) satisfies this approach.

MDO is an emerging optimization method that considers a design environment with multiple disciplines. The MDO has gained an increasing amount of attention since the end of Eighties and literature is abundant. The application of these techniques concerns almost exclusively the fixed wing domain. In the rotorcraft sector, the works of the Georgia Institute of Technology (e.g. [10]) can be cited among the rare examples. At ONERA, numerous works on rotor optimization both on aero-acoustics and aero-elasticity have been performed using high fidelity codes, studying one coupling among many others. The MDO potential is not completely exploited.

MDO methods can be classified in two groups;

- Single level: these methods use a non-hierarchical structure of disciplines with a global system optimizer. The most widely used methods are MDF (Multidisciplinary Feasible), SAND (Simultaneous Analysis and Design) or IDF (Individual Disciplinary Feasible).
- Multi levels: in this case each discipline is optimized before an optimization at system level. Commonly applied methods are CO (Collaborative Optimization) or BLISS (Bi Level Integrated System Synthesis).

The choice of the MDO formulation must be done by considering the system to be optimized, the complexity of models, the speed of execution, the criteria and constraints ...

Globally the multi-levels methods are more difficult to formulate and integrate than single level techniques. The last have a shortly execution time. For example CO and BLISS are better suited for the complex and demanding problems. For this study we consider first the All at Once technique. The multi levels techniques are not described in this study. Indeed the number of design variables and problem complexity do not justify the use of multi-levels MDO. However CREATION project will consider multi levels techniques like CO or BLISS depending on the sizing problem.

3.2. All at Once

All at once is a single level technique, also called SAND for Simultaneous Analysis and Design. It is the most basic solution to solve a MDO problem. Local design variables and constraints are moved to the system level. In consequence we create intermediate variables that are copies of true outputs from disciplines. They are independent and treated as design variables by the global optimizer. The coupling variables are put in a set of common variables. Thus the disciplines become virtually also independent and this decoupling allows the relaxation of coupled constraints. Analyses and optimizations are done at same time so each discipline only needs to run only once.

The main advantages of this technique are the simplicity and the speed of implementation. The design variables are controlled by a single user since they have only one optimizer. The disciplines experts have no control at local level. The major drawback to AAO is that the resolution problem grows in complexity with the number of disciplines and coupled variables.

To sum up, the AAO methods do not suit for a complex problem with a big number of design variables and disciplines. Yet for conceptual phases at early stage such as the present study, AAO method is appropriated.

The Fig 3 shows the organization of disciplines. At top-left two boxes represent the repository of variables and the system optimizer. There is no direct links between each discipline. It underlines the independence of the disciplines in the analysis method. All the dependences are taken into account at the global system optimizer level.

The Table 2 shows the nomenclature usually applied for MDO models

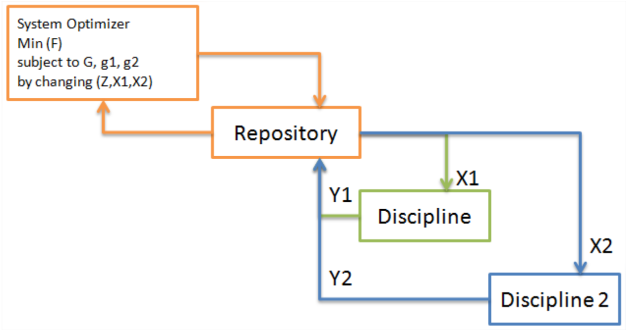

Fig 3: AAO scheme with two disciplines.

X^i	Local variables for disciplines i
Z	Common variables
Y^i	Output from discipline i
Y^{ij}	Interdisciplinary outputs
G, g_i, g_j	Global and local constraints
F	Objective function

Table 2: nomenclature for MDO models

3.3. AAO integration

Figure Fig 4 presents the organization used in this study. This scheme integrates two aerodynamics modules. Indeed, the study makes at the same time the optimization of two objectives (hover and low speed / SAR mission and cruse / Offshore mission). These indexes require two different mission flight points. Thus we need to duplicate the concerned disciplines. Table Table 10: Optimization summary table summarizes the objectives function, constraints and design variables used here.

The repository is an excel file containing copies of design variables and outputs. The other modules are computed in different languages such as Vb.net scripts, C++ or Fortran. They use ASCII files in input and output.

The optimizer is independent and can vary in function of the optimization requirement. The next part focuses on its choice.

The final integration uses ModelCenter© 10 environment. This software is a graphical environment for integration of models and design optimization. It uses a system of management of links between disciplines. This program is able exploring design space and finding best design thanks to several optimizers and engineering techniques (e.g. design of experiments, parametric studies, sensitivity analysis…).

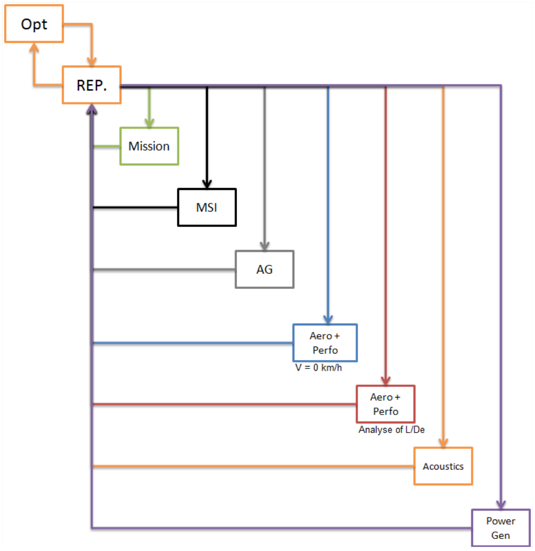

Fig 4: Organization of CREATION level 1 models in the AAO formulation.

3.4. Optimization

The optimization takes an important part of multidisciplinary problems. In common cases, the optimizer is a black box that needs inputs, constraints, objectives functions and their gradients eventually. The hard point of optimization is to converge to the global optimum design point. Indeed the optimizer can lead towards local optimum or enter in stationary evolution without converging.

In the multidisciplinary framework the disciplines are linked. Thus models aggregate complexity and can create non linearity. For instance the cruse performance index lift over drag ratio L/D_e (equivalent to the fixed-wing performance parameter) is in the case of a helicopter main rotor a function of the lifting force, the induced power and blade drag profile power themselves related to more or less complex Cxp and thrust formulations. With the overlapping of models it is difficult to ensure that an objective function is convex, differentiable or continue. The linearity of objective functions is an important specification to choose the optimizer. Furthermore codes can be very complex and have a high processing cost. In this case the number of iterations must be limited. In aeronautics most of variables are defined on restricted domains and unconstrained algorithms cannot be used. The discontinuity of variables may cause problem.

There are several methods that can be gathered in three classic domains:

- Gradient methods
- Gradient free methods
- Population evaluation methods.

The gradient methods are well known and very fast. However they require that the objective function is smooth. Due to the links between codes and disciplines, the continuity cannot be ensured in all cases. Furthermore these methods are very sensitive to the existence of local optimum and thus to the initial set of starting conditions. Most of gradients based techniques do not accept multi-objectives. Polak-Ribiere [11] (conjugate gradient) algorithm accepts several cost functions, but it needs unconstrained parameters and most of codes cannot allow that. However Sequential Quadratic Programming is often used with MDO [12].

Gradient free methods do not require the continuity derivability of functions. Among the choice of techniques, pattern search formulations are well adapted to poorly defined problems. These methods are heuristics. It uses a shape such as a cross where the current design point is at center. This point is perturbed in different directions for each dimension. When a better design is found, the current design point is moved to the new design. The perturbation step size is reduced and the pattern search is repeated until the step size becomes smaller than the convergence criteria (Fig 5). Hooke-Jeeves Pattern Search [13] is one of these techniques but we can notice more advanced methods such as Nelder-Mead [14] (also called simplex [15] method) or the asynchronous parallel pattern search.

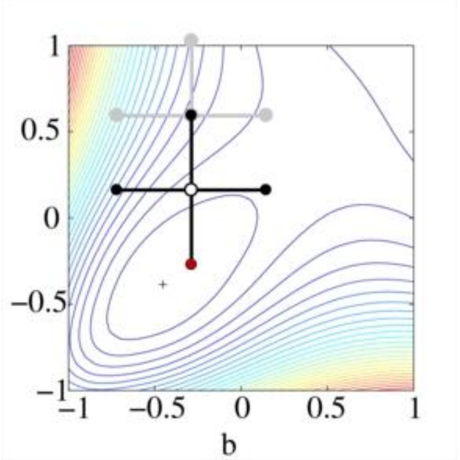

Fig 5: Pattern search example, the pattern is the cross and the new better design point is red. At next step the cross will moves on this point.

Hooke-Jeeves does not require continuous function. It is well adapted to noised function. In our case, programs may crash interrupting iteration optimization process. Indeed a crash of program is seen by the optimizer like a discontinuing function. This algorithm takes into account the range constraints of each variable but use only one objective. The minimization of rotorcraft total required power will use this technique by searching the optimal main rotor rotation speed (section 5.1).

Population evaluation approaches represent a subgroup of the meta-heuristics methods. Genetics and particles swarm algorithms are the most used. An important property of meta-heuristics is their adaptation to any problem. For example the search of the best design is a good imitation of nature evolution and selection. ModelCenter© proposes different genetic algorithms. They can use constrained and discontinuous variables, optimize with two or more cost functions and do not require any information on the form (mathematical properties) of the objective functions. The main disadvantage of genetic and particles swarm optimizers is the number of iterations to obtain the optimum solution. These methods are in principle not well suited for complex models as in aeronautics where most of calculation programs as comprehensive flight dynamics codes or CFD computations are slow. The interest of using meta-models or response surface models is then strengthened.

In the case of CREATION, low levels of modeling codes are simple and time of execution of each is less than a second. Thus the use of genetic or particle swarm algorithms is well adapted. The particle swarm optimization cannot manage several objectives whereas the main rotor optimization is multi-objective. Thus this technique is not tested in this study.

Table 3 summarizes our requirements and constraints for the choice of optimization algorithm with respect to available methods in ModelCenter©.

Optimization	Genetics	particle	Gradient free	Gradient
Multi-objectives	Yes	No	No	No
Constraints	Yes	Yes	No	No
Discrete variables	Yes	No	No	No

Table 3: Optimization requirements versus optimization algorithms.

3.5. Meta-modeling

The term meta-modeling is used for all models build from data (experimental or simulation results, database, statistics, etc.). Two sorts of meta-models are applied in the CREATION framework:

3.5.1. Reconstruction meta-models:

The low level models require both few input data and low computational cost. They can be based on: first principles, databases and simulations from upper modelling levels. For instance, a very first estimation of main rotor geometry can be calculated by the Architecture and Geometry module using polynomial regressions or neural networks derived from a rotorcraft databases.

Multilinear regressions are an approach to model the relationships between a scalar dependent variable Y and more explanatory variables called X. The goal of regression is the prediction and forecasting of an unknown parameter. Different works use these well known engineering techniques for pre-sizing rotorcrafts (e.g. [16], [17], [18]). The main difficulty is to obtain reliable databases. The database used here contains around 195 different helicopters for about eighty descriptive parameters. It was gathered thanks to the partnership between ONERA and DLR. The database contains all types of rotorcraft, from small ones such as the Aerokopter AK1-3 to bigger ones as the Mil Mi-26.

(3.1) $$Y = a.X^{\alpha}.X^{\beta}.X^{\gamma} \dots$$

(3.2) $$Y = a_n x^n + a_{n-1}x^{n-1} + \dots + a_1 x + a_0 x^0$$

In this study, a power law expression is applied for example to estimate some sizing constraints on the blade (see eq. (3.1)). Polynomial formulation is used for instance to evaluate the mean drag coefficient of blade. Indeed, Cxp is a polynomial expression of μ and Czm determined from simulations with a rotor blade element model (level 2).

Neural network is a mathematical model that is inspired by the structure and functional aspect of biological neural networks. It consists of an interconnected group of artificial neurons. In most cases, a NN is an adaptative system that changes its structure based on external or internal information that flows through the network during the learning phase. In the present study, neural networks are used for their prediction capabilities. It allows to link several inputs and outputs contrary to classical regressions that give only one output.

An example of neural network use is the estimation of some global important parameters of main rotor from some specifications. The model must provide the relationships between five inputs related to the main performances of a rotorcraft:

- Max takeoff weight (or payload weight),
- Required power for take off,
- Vmax (or others speed characteristics),
- Max range,
- Practical ceiling,

and the following three outputs:

- Number of blades,
- Main rotor diameter,
- Blade chord.

The database used to train the neural network includes 112 rotorcrafts. The neural network is a multilayer perceptron composed by one layer of three neurones with a linear function of activation. The results are showed in Table 4.

Parameters	SA 365N1	Results
b (nb of blades)	4	4
D (rotor diameter)	11.94	12.06
c (chord)	0.405	0.377

Table 4: results from an application of neural networks

Despite of these good performances, these models are not physical because the resulting equation is expressed with non-dimensional terms. So it is difficult to study the physics contained in these equations. These models can be useful for giving first estimates. However for innovation or optimization of rotorcraft concepts beyond the scope of the database, all these meta-modelling techniques can not overcome the limitation of the database from which they provide models.

Reduced models:

Several techniques use simulations of high fidelity models in order to derive simplified models. Response Surface Methodology (RSM) is one of them. This method explores the relationships between several explanatory variables and one or more results. The main idea is to use a sequence of design experiments to get a set of typical responses.

First, RSM needs to generate a distribution of input parameters. It is the design of experiments for which different sampling can be used. The most simple one is the orthogonal array which is a regular grid of n variables dimensions, but the distributions can also be developed over a random grid such as the Latin-Hypercube distribution. A mix of random and regular distribution can be applied. The random distribution is more adapted to stochastic problems in contrary to regular distribution that is used for well defined functions.

After all the expert model simulations, the response surface is computed. It consists in using regression and interpolation methods to construct the surface. Polynomial, radial basis functions or Kriging techniques may be applied. We choose the last one in the present study.

Kriging is a stochastic technique of spatial interpolation. It allows eliminating statistically inconsistent or incoherent points. Thus the aim of Kriging is to estimate the value of $\hat{y}$ at a given point x using a linear combination of neighbour sampled values y_i. The λ_i coefficients are the weights. It gives the solution in order to obtain a non-biased prevision with minimal variance. The factor $\epsilon(x)$ is the stochastic factor. More information about Kriging methods can be found for example in references:[19], [20] and [21]

$$\hat{y}(x) = \sum_{i=1}^{n} \lambda_i(x) y_i + \epsilon(x) \tag{3.3}$$

The performances of Kriging are very good for our problem. RSM and Kriging are used in the part 5.1.

To sum up, both reconstruction and reduced meta-modelling techniques have a practical use in the present study. At low modelling-level, physics is not entirely modelled, some important constraints can be unknown. These constraints can be implicitly present in the database. Constructing a meta-model on a database of existing rotorcraft allows taking into account some of them. The second approach is applied for simplifying the use of complex and high computational cost models for instance for flight dynamics (e.g. HOST [9]) or for aerodynamics (vortex wake models or CFD later). The RSM can be used in different optimization loops instead of many calls of the expert models.

4. Main Rotor optimization

4.1. Mission and requirements

The Mission module gathers all the flight points for the considered rotorcraft. Thus it defines a significant part of the pre-sizing requirements. The main rotor will be optimized to achieve the best performances over the design missions.

Typical missions of the Dauphin are Search and Rescue (SAR) or offshore, but some evolutions of Dauphin achieve fighting or offshore missions. The mission gives specification, requirements and trend design information. SAR missions give a preference to hover and low speeds performances as stability, hover required power or noise. At the opposite offshore mission will favor action radius, low fuel consumption or fast cruise speed. These trends of design are sometimes conflicting. So in a multi-mission context, the choice of sizing points is very important. Sizing with only one mission can obviously upset the balance of design.

The entire mission spectrum is taken into account by considering an average mission. Verlut and Dyrla (Eurocopter) [22] have proposed representative percentage of the three main flight conditions through typical helicopter missions. It helps to balance the sizing. Percentages are detailed in Table 5.

Average Mission Design	
Hover	10 %
Cruise – Vbe	30 %
Cruise – 220 km/h	60 %

Table 5: percentages mission with three main phases

In order to evaluate the new rotorcraft we use realistic missions: SAR and offshore. The mission plans are presented in Table 6 and Table 7.

step	OFFSHORE – Phases Wrc = 4000 kg	End X km	End Z m	Vh m/s	Vz m/s
1	Take-off from Clear heliport	0	20,0	0,0	0,05
2	Climb to cruise altitude	1.67	318,1	40,0	2
3	Cruise	28.1	914,4	61,1	0
4	Descent to LDP	307	638,1	40,0	-2
5	Landing on heliplatform	310	56,4	0,0	-0,05
6	Take-off from heliplatform	310	64,9	0,0	0,05
7	Climb to cruise altitude	312	354,7	40,0	2
8	Return flight	338	914,4	61,1	0
9	Descent to LDP	617	619,8	40,0	-2
10	Descent from LDP to pad	621	16,8	20,6	-2,032
11	Landing on Clear Heliport	621	1,5	0,0	-0,05

Table 6: Offshore mission

step	SAR – Phases Wrc = 3200 kg	Pos X km	Pos Z m	Vh m/s	Vz m/s
1	TO from Clear heliport	0	20	0,0	1
2	Climb to cruise altitude	5	1000	40,0	2
3	Cruise	11.7	1000	61,1	0
4	Descent to search zone	110	100	40,0	-2
5	Search	124	100	40,0	0
6 - 13	Rescue 1 - 8 Payload : 8 x 100 kg	182	100	0,0	0
14	Climb to cruise altitude	187	1000	40,0	2
15	Return flight	194	1000	61,1	0
16	Climb to LDP	297	50	40,0	-2
17	Climb from LDP to pad	298	20	20,6	-2,03
18	Landing on Clear Heliport	298	0	0,0	-1

Table 7: Search and Rescue mission

4.2. Objectives of optimization

The objectives, cost functions or criteria of optimization must be linked to mission phases. Indeed, the requirements for the best performances of main rotor are depending on the flight point. In this study we consider both hover and forward flight performances.

Classically, hover performances are characterized by the lifting efficiency η_s (or figure of merit) of the main rotor. η_s is defined as the ratio of theoretical induced power over actual required power. It is limited to a maximum of one.

$$\eta_s = \frac{P_{ind_0}}{P_{reqMR}} \tag{4.1}$$

Maximizing η_s corresponds to optimize the main rotor for hover but it does not mean that the required power is minimal. This result is not conflicting but if the final goal is to minimize the power needed over the mission, this index is not adapted. That is why our index of performances in hover will be the required power in Hover Out of Ground Effect (HOGE) condition.

$$P_{req}(V = 0) = Pind + Pblade \tag{4.1}$$

For the cruise phases the equivalent lift to drag ratio L/D_e is used as performances index. It is introduced in the NDARC tool [3]. Commonly Lift to drag ratio is calculated for the entire rotorcraft lift and drag. But in our case we only consider the main rotor. Thus in the power balance framework only the induced and blade profile drag powers are used:

$$L/D_e = \frac{T.V_h}{P_{ind} + P_{blade}} \tag{4.3}$$

We have two performances index, one for hover, the other for advancing flight thus the optimization must be compatible with multi-objective. Yet that is for testing optimization techniques, since both criteria can be reduced to one: the minimization of the main rotor required power (Pind + Pblade).

4.3. The choice of variables

In Section 2.1 the state of art of the level 0 models has been presented. They will be used here as a first pre-sizing exercise for optimizing the main rotor. Variables associated to this system are the rotor radius, chord, number of blades and rotation speed. Some very important characteristics such as the blade twist, airfoils, chord variation, etc. are not taken into account in this first step of the pre-sizing. They require blade element models (level 2). Thus the improvement of performances will be done by considering only the dimensions and speed of the main rotor: R, c, Nr.

Two main types of constraints are considered hereafter, aerodynamics and structural. But the study cannot does pretend to consider an exhaustive list of constraints.

4.4. The structural constraints

Once the variables selected, the next step is the characterization of constraints. This is crucial to obtain realistic results. If the constraints are badly chosen, the results can be mathematically correct but physically wrong. It is a hard point of the study because on low level of description, all the physics in every involved discipline can not be caught by simple models. At level 0, the structure of the rotor is not considered but this discipline imposes some constraints:

- Flap frequency
- Stiffness of materials
- Fatigue
- …

For example, an optimization of rotor dimensions would give in hovering conditions a very big radius, because the induced power decreases with increasing rotor radius, but structurally it may be impossible. The article of C. Russell and W. Johnson illustrates this fact [23].

Without a finest description of rotor dynamics, we cannot take into account structural constraint. In order to solve this issue, a database with meta-modeling techniques is used. The database is composed by approximately 195 different rotorcrafts. 170 of them have enough main rotor information to be used. The rotorcraft database is made up of many rotorcrafts designed between 1943 until today. It represents all scale of weights, power and geometry. The Table 8 shows some data about it.

Characteristics	Range
Wmto (kg)	622 – 43700
Pto (kW)	97 - 16776
First flight	1943 – 2011
Main rotor Diam. (m)	6.84 – 35
Solidity (SU)	0.03 – 0.14
Disc Loading (kg/m²)	12.91 – 73.70
Blade Loading (kg/m²)	157.80 – 708.06

Table 8: overview of some database parameters overview

The assumption is that the optimization of main rotor studied here must produce a result compatible with the database. So structural constraints are extracted from the database.

As Fig 6 shows, correlation between the blade loading and aspect ratio is closed to 0. Thus the contribution of the aspect ratio to the structure constraints can only be set in terms of minimum and maximum values at least as regards to the database. Table 8 presents the low values obtained from a correlation study of the blade aspect ratio with other parameters such as weights (empty,max take off), geometrical main rotor parameters (chord, radius) or performances (blade loading, …). However, reference [23] indicates that the aspect ratio must be between 13 and 18, although more constrained this result is compatible with our database information giving about 9 and 25.

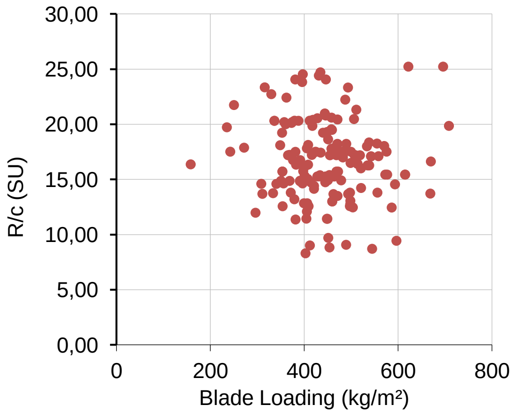

Fig 6: distribution of aspect ratio R/c wrt. blade loading

	WEmpty	*Wmto*	*2.R_mr*	*Rotor Area*	*Chord*	*R/c*
R/c	-0,113	-0,099	-0,126	-0,036	-0,655	1
	solidity	***DL***	***BL***	***PL***	***bcR***	
R/c	-0,4713	-0,380	-0,045	-0,431	-0,136	

Table 9: cross correlation between aspect ratio R/c and other parameters.

4.5. The aerodynamics and acoustics constraints

The aerodynamics imposes some of the most important constraints on rotorcraft. An upper limit is given in terms of speed by the maximum blade tip speed: Vtip + Vmax. The speed must not exceed about 0.9.Cson. Beyond this blade tip speed, the rotor is with compressibility and transonic flow effects near the tip of the advancing blade side. So if Nr and R are chosen as optimization variables, we must take into account this upper limitation of blade tip speed. The lower limit comes from the stall effect on the blade retreating side. When the advance ratio µ equals 1, all the retreating blade is in reverse flow condition ($\mu = Vh/\Omega R$).

The acoustics disciplines can give some additional constraints or being an objective (“cost function”). It depends on the designer point of view and rotorcraft specification. Acoustics is an important field of improvement. It is a design driver of the CREATION project. Yet in this first pre-sizing exercise, a cost function on the acoustics has not been applied, although the acoustic factor could be used to select a point on the optimization Pareto front.

Table 9 summarizes all objective variables and constraints considered in the optimization.

4.6. Side constraints

Each variable are bounded. The range of variation must be large enough to let the optimizer explore the entire solution space. The extreme solutions will be brushed aside by constraints.

The ranges of variation of the optimization variables are set to explore the domain around the reference helicopter values. The main rotor radius varies between 4 m and 6.50 m. The original size of SA 365N main rotor radius is 5.956 m. The chord of main rotor blade varies between 0.2 m and 0.6 m (0.405 for SA 365N). The rotation ratio variation amplitude is 50% so Nr varies between 175 rpm and 525 rpm.

4.7. Optimization requirements.

As detailed previously, the optimization is multi-objectives, multi-variables and constrained. Table 9 summarizes all objectives variables and constraints considered in the optimization.

<table>
<tr><th colspan="2">Objectives Functions</th></tr>
<tr><td>$\min\,(Preq\ @\ Vh = 0)$</td><td>Flight performances</td></tr>
<tr><td>$\max\,(L/D)$</td><td>Flight performances</td></tr>
<tr><th colspan="2">Design variables</th></tr>
<tr><td>R</td><td>Architecture</td></tr>
<tr><td>c</td><td>Architecture</td></tr>
<tr><td>Nr</td><td>Architecture</td></tr>
<tr><th colspan="2">Side Constraints</th></tr>
<tr><td colspan="2">$R \in [4; 6.5]$,
$c \in [0.2; 0.6]$
$Nr \in [175; 525]$</td></tr>
<tr><th colspan="2">Inequality constraints</th></tr>
<tr><td colspan="2">$Nr.R.2\pi/60 + V_{\max} < 0.9.C_{son}$
$13 < R/c < 18$</td></tr>
</table>

Table 10: Optimization summary table.

5. APPLICATION

In previous parts several techniques have been presented for optimizing and deriving new models. Some of these methods are applied here to the present practical problem in three main steps. The first step is the determination of an optimal rotor. The second step is the selection of solutions. Finally the selected rotorcraft designs are tested and compared on a realistic mission.

5.1. First step: Optimization

5.1.1. Main rotor rotation ratio

Usually the main rotor rotation ratio of rotorcraft can be considered as constant. Some new concepts introduce important variations of Nr in order to increase the flight envelop towards high speeds (e.g. X2 and X3 demonstrators) or for reducing the fuel consumption thus leading to increased endurance and range of action. The drone A160 Hummingbird (Fig 7, [24]) of Boeing is one of them. This technology is pretty hard to be adapted to all engines. It products deep modifications of main gear box and turboshafts. Despite of these technological implementation difficulties, it seems interesting to study the dependency of the optimal rotation ratio with respect to the rotorcraft speed.

Fig 7: A160 Hummingbird drone *Photo: Boeing*

Preliminary works for CREATION underlined the importance of minimizing Nr to reduce the total required power [25]. This study found a gain of 15.4% for the fuel consumption over a classical mission profile by reducing the rotation speed about 40%.

In our present level 0 model, the power quantities impacted by Nr are the induced power (through the induced factor) and the blade drag profile power. This last is the main contribution. Thus optimizing the total required power in function of Nr comes down to minimize the blade drag power P_{blade}. The P_{blade} (eq. 5.1) is a function of main rotor parameters and Cxp: the blade mean drag coefficient (eq. 5.2). The present blade mean drag coefficient is a polynomial function of μ (eq. 5.3) the advancing ratio and Czm the mean blade lift coefficient (eq. 5.4).

$$P_{blade} = \frac{1}{8}.\rho.R.b.c.Cxp.(\Omega.R)^3 \tag{5.1}$$

$$\begin{aligned} Cxp = \quad & a \,+\, b.\mu^2 \,+\, c.\mu^6 \,+ \\ & (d \,+\, e.\mu^2 \,+\, f.\mu^6\,) * Czm \,+ \\ & (g \,+ h.\mu^2 \,+\, i.\mu^6\,) * Czm^2 \,+ \\ & (j \,+\, k.\mu^2 \,+\, l.\mu^6\,) * Czm^6 \end{aligned} \tag{5.2}$$

$$Czm = 6.T/(\rho.R.b.c.(\Omega.R)^2) \tag{5.3}$$

$$\mu = V_h \,/\, (\Omega.R) \tag{5.4}$$

Alternative Cxp formulations have been tested during preparation works of CREATION. The first one (eq. 5.5) is the common used formulation. The second one (eq. 5.6) is used in [25].

$$Cxp2 = (a + b.Czm^2).(1 + 5\mu^2) \tag{5.5}$$

$$Cxp = (a.Czm^6 + b.Czm^2 + c.Czm \,+ d)\,.\,(1 + 5\mu^2) \tag{5.6}$$

The formulation of Cxp has an important impact for the minimization of P_{blade}. Indeed after first optimization we found optimal Nr reduction about 10% and not the 40% predicted by [25]. The explanation is the formulation of Cxp. In most of the classical expressions of Cxp (e.g. eqs. 5.3, 5.5 and 5.6), exponent affecting ΩR is negative. Hence in some cases (typically for Cxp of eq. 5.5) the effect of $(\Omega R)^3$ in P_{blade} is not surpassed by the effect of ΩR in Cxp and the P_{blade} increases as ΩR. The Fig 9 shows that. The contribution of ΩR predominate in P_{blade} and the minimal P_{blade} is reached for the minimal ΩR (for eq. 5.5). The Fig 8 illustrates the currently used Cxp formula (5.3). It has no singularity issues, the minimal P_{blade} is not obtained for the minimal ΩR. These results stay true for different speeds.

The conclusion of this discussion is that the optimization of Nr is dependent of Cxp model. Furthermore notice that the induced power varies as a function of Nr (through the induced correction factor) in the present level 0 model (whereas it was not the case in the previous study [25]). P_{ind} is inversely proportional to the Nr. Thus the variations of P_{blade} and P_{ind} are inverted in function of Nr. That produces interest conflicts during the optimization.

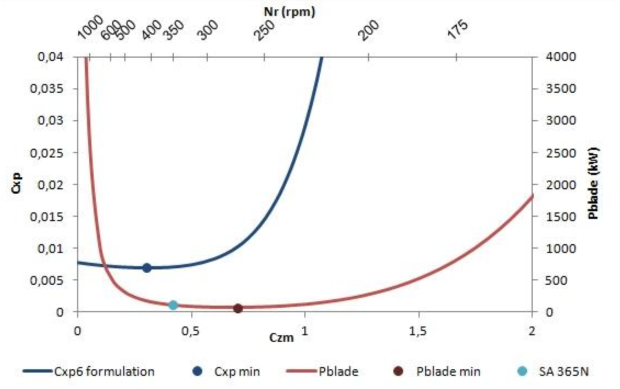

Fig 8: plot of Cxp and Pblade in function of Czm at μ = 0. The top x axis corresponds to a conversion of Czm in terms of Nr for the SA 365N rotorcraft. Cxp is expressed with the equation 5.2

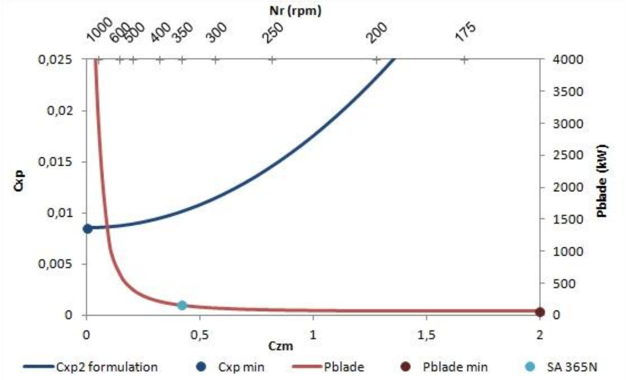

Fig 9: Same plot as above. Cxp is expressed with the equation 5.5.

For this optimization, the required power is minimized by changing the rotation speed for every rotorcraft speeds and a fixed rotor geometry (b, c, R). The Hooke-Jeeves method is performed. Under certain conditions of rotational and forward speed, the codes can crash so this method is well adapted. The optimization is done at sea-level in standard atmosphere conditions (ISA 0) for the SA 365N max takeoff weight: 4000 kg. A further step would be to apply the same procedure but for different masses and altitudes.

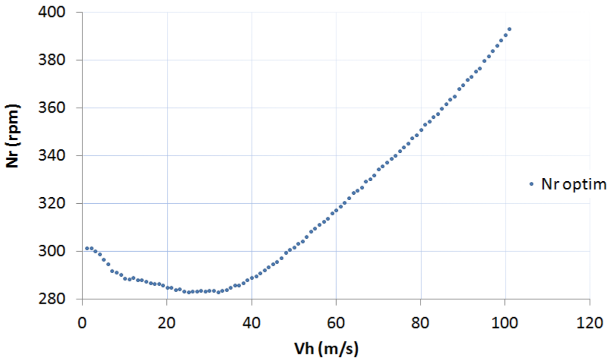

Fig 10: Variation of optimal Nr in function of advancing speed.

The optimization gives a dataset which allows determining a Response Surface. The RS is computed using a Kriging method as described in section 3.5. RS is used to provide an optimized Nr for every points of the flight mission (Fig 10). The performances of Kriging reconstruction are good with an adjusted coefficient of determination equal to 0.9996 in contrary to polynomial law which makes consequent error at low speeds (Fig 11).

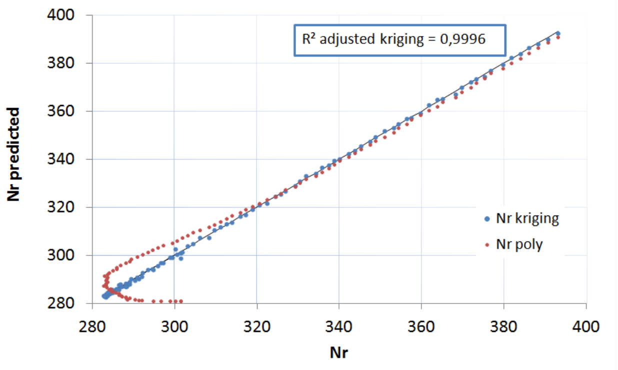

Fig 11: Response surface performances for polynomial and Kriging reconstruction.

Depending on the forward speed, the gain for the total required power can be significant with a maximum around 8% at 35 m/s.

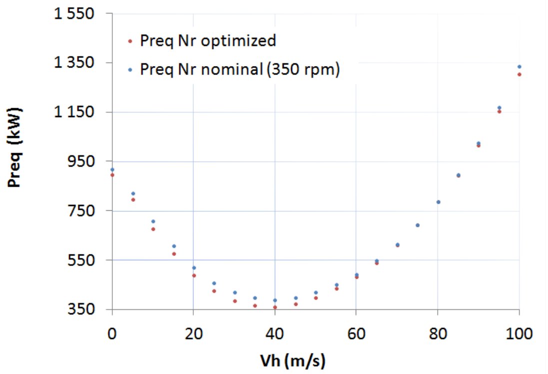

Fig 12: Comparison of required power in function of advancing speed for a nominal and optimized Nr.

5.1.2. Main rotor chord and radius.

We have seen in the part 0 that the genetic algorithm is able to respect our optimization requirements namely multiple constraints and variable side constraints. These constraints are defined in the previous part 4. The genetic algorithm used is the Darwin method.

The genetic algorithm begins to define a population of vectors (c, R, Nr), designated as “individuals” (phase of initialization). For each of them the response ($Preq_{MR}$ $(v = 0\ km/h), L/De$) is calculated and the best are selected (phase of selection). The best individuals are used to produce a second generation by reproduction. “Children” are mutated to introduce a variability. Generally this mutation enables the optimizer to avoid local optimum. The new generation is analyzed again. From generation to generation the vector chosen by the algorithm produce better responses. After a certain number of generations which do not improve the pareto front, the optimization is stopped. The optimization parameters are summarized hereafter:

- Population size : 50

- Convergence Criterion: generations without improvement
- Maximum Generations: 1000
- Generations without Improvement: 2
- Selection Scheme: multiple elitist
- Preserved Designs: 15
- Operator Probabilities
  - Discrete Variable Crossover: 1.0
  - Discrete Variable Mutation: 0.05
- Constraint Tolerance
  - Maximum Constraint Margin: 0.05
  - Percent Penalty: 0.5
- Number of Top Designs Stored: 43

These algorithms are used in 2 configurations. One is the c and R optimization, Nr being optimized with the previously described method. The second one is a full optimization of c, R and Nr. The following figures present the results of these optimizations with the corresponding Pareto fronts. The objectives $\min(Preq)\ at\ V = 0\ km/h$ and $\max(L/De)\text{at } 220 \text{ km/h}$ are calculated at ISA 0 and $Wmto = 4000\ kg$.

The Fig 13 and Fig 14 shows the results of the genetic optimization (red points) and their Pareto front (blue points). The design chosen points are in black.

The gain in comparison with the SA 365N are displayed in the Table 11. The optimization of c, R and Nr seems to give better results but for c, R optimization, the Nr is not optimal.

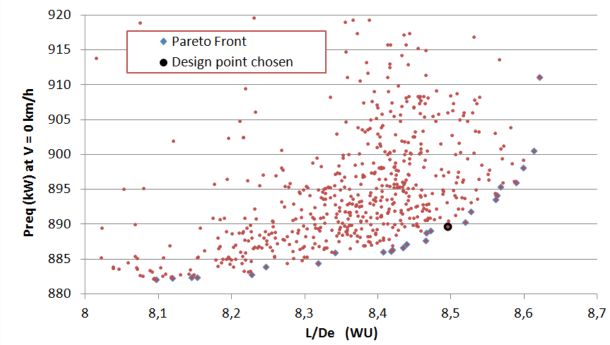

Fig 13: Optimization with a variation of c and R.

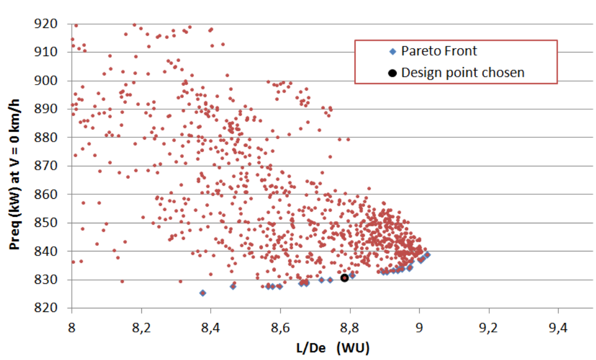

Fig 14; Optimization with a variation of c, R and Nr.

	SA 365N	Optim c, R	Optim c,R, Nr
Preq_HOGE	917	882 – 911	825 – 838
L/De @ Vh=220km/h	8,15	8,09 – 8,62	8.37 – 9.02

Table 11: gains for each optimization in comparison with the SA 365N.

For each new design, the weights of rotor system are calculated (blades and hub). They have an important impact on the weight of the empty rotorcraft. In order to keep the maximal take-off weight constant to set up the comparisons, the variation of design empty weights are compensated in the loaded fuel quantity. After these optimizations, we choose the rotorcraft candidates into the Pareto fronts.

5.2. Second step: Selection of design

The optimizer does not favor an objective function than another. However the choice of a balanced design should be adapted to a set of missions or requirements.

Evaluation criteria have the same weight. On the Pareto front none of the objective functions can be improved without degrading one or the other. The choice is made by external consideration wrt. the optimization criterion. It can be secondary constraints or associated results. In the present case, we propose to calculate the average of the objectives performances on the Pareto front in order to choose the closest solution. Another approach will be to weighting results in function of mission spectrum. The parameters are indicated in the Table 12. In order to simplify the reading, we call the rotorcrafts with optimization of (c, R) and (c,R,Nr) respectively: “365N cR” and “365N cRNr”. When the rotation speed is optimized, the rotorcraft has the extension Nr opt, in other case Nr nom for nominal.

	c (m)	R (m)	Nr (rpm)
365N cR	0.3477	6.233	Nominal (350)
365N cRNr	0.3837	6.5	278.2

Table 12: configurations selected for evaluation

For each configuration, global performances are calculated. The calculations use the CREATION level 0 models. Global performances are:

- Total required power versus advancing speed
- Required power for hover flight: Pto (kW). (This power takes into account losses).
- Best efficiency speed: Vbe (km/h)
- Best range speed: Vbr (km/h)
- Maximal range at Vbr: Dmax (km)
- Maximal endurance at Vbe: Emax (hr)
- Delta of Weight: weight added or subtract in consequence of the modification of blades and hub: ΔWrot (kg). To remind this delta of weight is sent back to the fuel weight.

These performances are summarized in the Table 13 and figure 15. Results are rounded to the unity.

Rotorcrafts SA 365N…	Vbe Km/h	Vbr Km/h	Pto kW	Dmax km	Emax hr	ΔWrot kg
Nr nom	145	205	933	762	4,54	0
Nr opt	145	194	901	764	4,77	0
cR Nr nom	145	205	899	798	4,73	-24
cR Nr opt	145	194	872	803	5	-24
cRNr	144	188	835	751	4,77	+23

Table 13: Synoptic table of performances of selected rotorcraft after optimization.

Until around 220 km/h the “365N cRNr” configuration is the less power consuming rotorcraft. But the 365N cR with optimized Nr proposes more advantages:

- The required powers are closed to the best until 220 km/h and give better performances above.
- The main rotor is lighter.
- Dmax and Emax are maximal.

In this academical study, the “365N cR – Nr opt” is for these reasons the best rotorcraft of these optimizations. The next step brings face to face missions and machines.

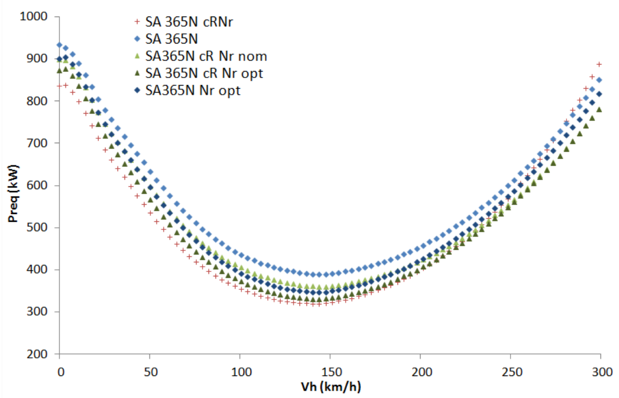

Fig 15: Required power in hover and level flights.

5.3. Third : evaluation on Missions

The chosen design is evaluated on two missions: SAR and Offshore. These missions are described in Table 6 and Table 7. Each of them is composed of classical helicopter flight phases:

- Take off from clear heliport
- Hover
- Climb to cruise altitude
- Cruise
- Descent to landing decision point
- Landing.

Missions are different in duration of these typical steps and missions tasks. SAR mission has for objective to rescue some persons. Thus during the mission the helicopter spends an important time in hover and low speeds. The weight of several bodies can increase the rotorcraft mass. Offshore platform are situated at few hundred kilometers from coast. So cruise phases predominate on the flight time.

The interest of mission evaluation is to study the fuel consumption of different rotorcraft and to compare them with a reference. In our case, the reference is the SA 365N Dauphin described in the previous parts.

Mission fuel, weight and power computations are made with the CREATION platform and the level 0 models.

5.3.1. Balance

The Table 14 and Table 15 summarize the results. The figure 16 and 17 shows the variation of main parameters on each step.

Analysis of mission results shows that the optimization of Nr has a small effect in the present study. Indeed the gain of fuel saved at offshore mission end is about 0.9 % and 1% for respectively “365N Nr opt” and “365N cR Nr opt”. For SAR mission gains increase to 2.4 and 2.3 percents.

The major improvement comes from the optimization of main rotor chord and radius: 3.3% of fuel saved between “365N Nr nom” and “365N cR Nr nom” and 4.3% if in addition Nr is optimized for the offshore mission. The same comparisons give 2.1% and 3.6% for the SAR mission.

The “365N cRNr” proposes good performances in terms of final rotorcraft weight and required power. However due to the bigger rotor radius the rotor weight is higher thus the fuel capacity is reduced. That is why the consumption is low but the percentage of fuel saved not so good.

Mission :	**Offshore**			
Rotorcraft 365N…	Wr at end (kg)	Wfuel saved (%)	Wfuel cons. (kg)	Preq mean (kW)
Nr nom	3327	25.7	673	476
Nr opt	3335	26.5	665	458
cR Nr nom	3341	29.0	659	460
cR Nr opt	3350	30.0	650	440
cRNr	3350	26.3	650	433

Table 14: offshore main results for each configurations

Mission :	**SAR**			
Rotorcraft 365N…	Wr at end (kg)	Wfuel saved (%)	Wfuel cons. (kg)	Preq mean (kW)
Nr nom	3536	48.8	464	468
Nr opt	3550	50.2	450	449
cR Nr nom	3544	50.9	456	453
cR Nr opt	3559	52.4	441	431
cRNr	3562	50.4	438	426

Table 15: SAR main results for each configurations

Difference of fuel consumption between these variants of rotorcraft is marginal. We observe maximal gains of 3.6 and 4.3 % of fuel saved for respectively SAR and offshore missions. These results were expected. Indeed the required power variation is not significant: on the mean of missions 40 kW.

The optimization has not an important effect here. Several hypotheses can explain that:

- Designs are maybe too much conservative and extreme solutions could give better results. However the low level of rotorcraft description in the level 0 model requires carefulness. In fact all the constraints are not considered. That could lead to unreal or bad results if wider ranges are explored.
- The optimization objectives are not good pre-sizing functions. Search of more relevant pre-sizing cost functions is a goal of CREATION.
- Other designs within the Pareto front could produce better results in function of the mission. The “365N cRNr” chosen is an optimum but it is possible to choose more “extreme” designs on this front giving more effects. These last could produce better results in hover or forward flights.
- The SA 365N is already well optimized for these missions and the optimum is not far from this reference existing solution.

6. CONCLUSION

Pre-sizing is synonym of first stage of preliminary conception. At this step very few data are available about the rotorcraft, hence the models of description have to be simple. In parallel, the pre-sizing requires optimization to perform a design adapted to the specifications. These first optimizations needs simple models for exploring quiclkly a wide field of first possible solutions. The paper illustrates the interest of several meta-modeling and optimization techniques.

Multidisciplinary Design Optimization (MDO) is an adapted framework dedicated to complex system. The CREATION project investigates precisely the benefice of these methods.

The practical context for this investigation on the methods is focused on the main rotor pre-sizing. In the case of multi-objectives optimization, the genetic algorithms (GA) have proved their efficiency. Furthermore GA needs low cost computing models. That is compatible with level 0 models of CREATION. Non gradient methods are advised in cases of multidisciplinary problems where continuity of functions is not ensured.

High fidelity models cannot be executed thousands times. Reduction modeling techniques allow their use by simplifying complex models. In this way, the coupling between optimization and reduction methods such as Kriging was useful. The other interest of surrogate models is to catch underlying relationships and constraints contained in the database of existing rotorcraft. All these techniques were tested successfully although the results on mission evaluation do not give important improvement. That must be seen as a good sign of the maturity of the models and methods. Indeed, the results are finally not too far from the existing Dauphin helicopter design, although the present study remains an academical one.

Optimization and regression techniques do not free us to master the subjacent physics. The optimization result is intrinsically linked to the chosen constraints and objectives. All these tools allow exploring more easily and rapidly solutions which always need the engineer judgment.

Future work will go further on the study of the MDO methods. AAO was tested but must be compared with other techniques. That will be investigated in the context of the second milestone of the CREATION project: the pre-sizing of a complete helicopter.

7. AKNOWLEDGEMENTS

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9. APPENDIX

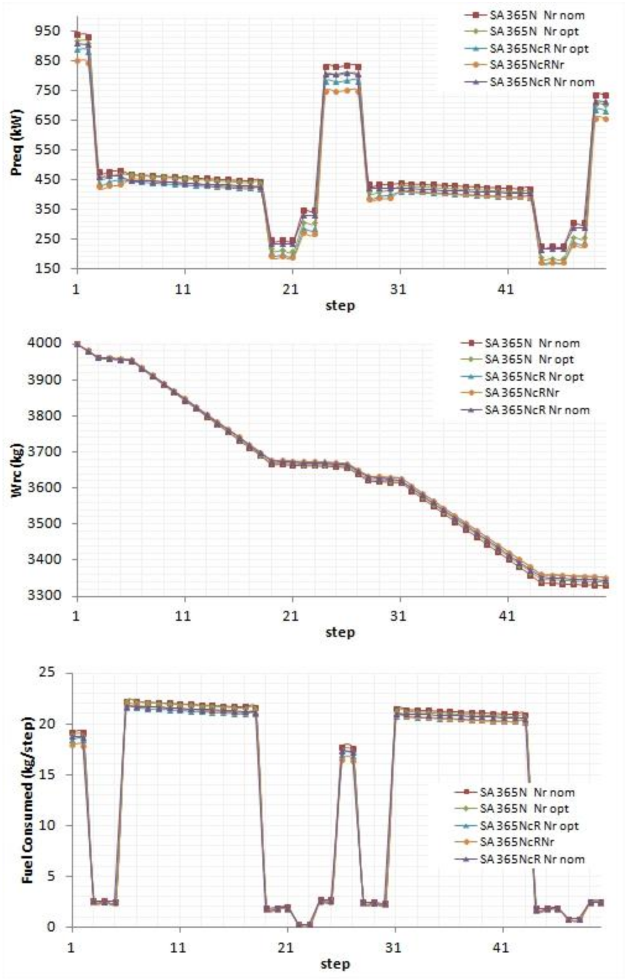

Fig 16: Results for offshore mission with respect to the mission steps. The first figure at top shows the variation of required power, the second one indicates the rotorcraft weight and the last at bottom presents the consumed fuel during a step. As can be seen the fuel consumed is high during the cruise although the required power is low. This is because these steps last longer in time in comparison with hover phases.

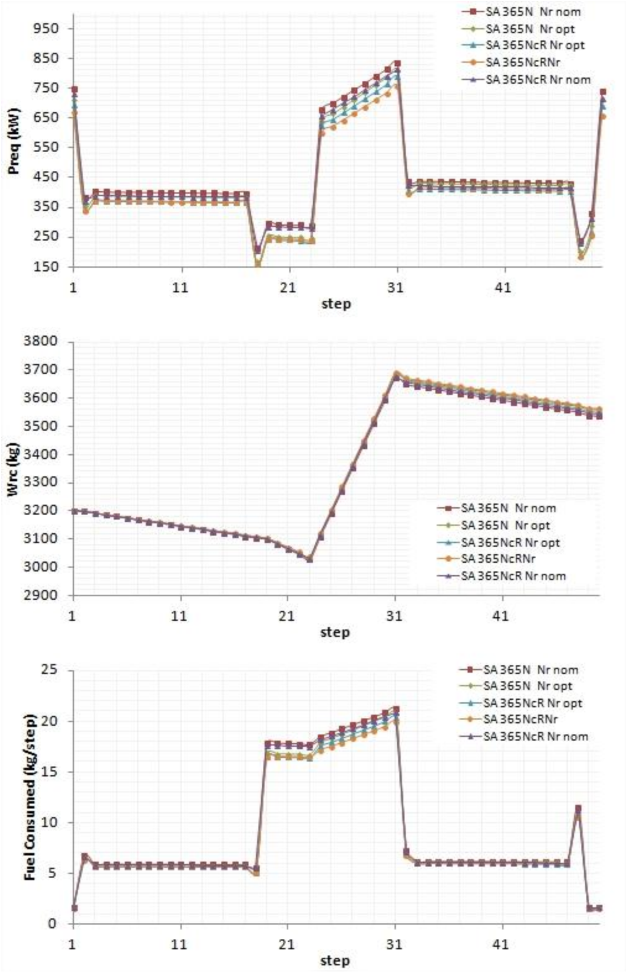

Fig 17: Same as figure 16 but for SAR mission. The increasing of weight at middle of the mission is due to the boarding of rescues. The rescue steps are achieved in hover and each boarding run five minutes. Thus the consumed fuel is important.