The C.R.E.A.T.I.O.N. project for rotorcraft concepts evaluation: The first steps

P.-M. Basset, A. Tremolet, F. Cuzieux, C. Schulte, D. Tristrant, T. Lefebvre, G. Reboul, M. Costes, F. Richez, S. Burguburu, D. Petot, B. Paluch

Onera - The French Aerospace Lab

FRANCE

basset@onera.fr

Notation

b	number of blades,
c	blade chord, (m)
C_{xb}, C_{xp}	blade airfoil drag coefficient
CxS_{af}	airframe equivalent drag area, (m²)
C_{zm}	blade mean lift coefficient
Dmr	main rotor diameter, (m)
Dtr	tail rotor diameter, (m)
HOGE/HIGE:	Hover Out of Ground Effect, Hover In Ground Effect
$K_{MR/F}$	coefficient of interaction between main rotor downwash and fuselage
k(V)	ratio between tail rotor required power and main rotor required power
κ_{mr}	Correction factor for induced power
L_{af}	airframe length, (m)
M or Gw	gross weight, (kg)
MCP	Maximum Continuous Power delivered by engine(s), (kW)
MTOW	Maximum Take-Off Weight, (kg)
µ	advance ratio: $V_h/(\Omega.R)$,
OPR	Overall Pressure Ratio
Ω	rotor rotational speed, (rad/s)
P_{req}, P_n	Total required power, (kW)
P_{reqMR}	Main rotor required power, (kW)
P_{reqTR}	Tail rotor required power, (kW)
$P_{induced}$	Induced power needed, (kW)
P_{blade}	Blade drag profil power, (kW)
$P_{airframe}$	Airframe drag power, (kW)
r	radial position of a point on the rotor, (m)
R	Main rotor radius, (m)
ρ, g	air density (kg/m^3), gravity constant (N/kg)
σ	main rotor solidity,
SFC	Specific Fuel Consumption,
TOP	Takeoff power delivered by engine(s), (kW)
V	rotorcraft speed, (km/h)
V_{ne}	Speed never exceed, (km/h)
V_{max}	maximum rotorcraft speed, (km/h)
V_{be}, V_y	best endurance speed, (km/h)
V_{br}	best range speed, (km/h)
V_{im}	mean induced velocity normal to the rotor, (m/s)
V_{i0}	Froude rotor induced velocity in hover (m/s)
W_u, $W_{crew\&pax}$, $W_{payload}$, W_{fuel}	respectively useful weight and weights for crew and passengers, payload and fuel, (kg)
wrt.	with respect to

Abstract

*ONERA launches in January 2011 its federative multi-departments research project C.R.E.A.T.I.O.N.: **C**oncepts of **R**otorcraft **E**nhanced **A**ssessment **T**hrough **I**ntegrated **O**ptimization **N**etwork. The main goal is the development of a multidisciplinary computational platform for the evaluation of rotorcraft concepts. The evaluation concerns flight performances and environmental impacts (acoustics, fuel consumption, etc.). The paper presents the goals, the approach and the first steps in the development of this dedicated platform.*

Introduction

After several years of preliminary studies, ONERA launches in January 2011 its federative multi-departments research project C.R.E.A.T.I.O.N.: Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network.

The main goal is the development of a multidisciplinary computational platform for the evaluation of rotorcraft concepts. The evaluation concerns flight performances and environmental impacts (acoustics, fuel consumption, etc.).

The purpose of that work on own funding is both:

- to provide ONERA methods and tools for assessing and contributing to the innovation in the field of rotorcraft,
- and as a corollary, to have a dedicated computational mean for the expertises of rotorcraft concepts for the French government, the European Union, the industry.

The CREATION platform must be able to evaluate any rotorcraft concept whatever the level of details in the description data available. That includes the cases for which very few data are known, for example: when only an idea of new concept and of its potential application must be assessed or when only an expression of needs is given by future operational users. Therefore the tool must cope with the preliminary conception and pre-sizing problems.

Hence, several levels of modelling will be included allowing to assess a rotorcraft from the appropriate modelling level depending on the first data available which can be: very poor in the case of a rotorcraft to be conceived or high in the case of the expertise of an existing rotorcraft.

Presented at the 37th European Rotorcraft Forum, Italy, September 13-15, 2011.

The need for that kind of tool comes from the context of these last years. The worldwide rising interest for Rotary Wing Uninhabited Aircraft Vehicles, (RW-UAVs), has strongly increased the number of projects of rotorcraft concepts. The costs and risks of developments are less prohibitive than in the case of inhabited aircraft. That contributes to the enrichment of the already wide variety of rotorcraft concepts by revisiting old alternate concepts with new technologies (e.g. the tail-sitters) or by creating new concepts.

In the field of manned or inhabited rotorcraft, there is also a renewal of interest for alternate concepts with respect to the single main rotor - single tail rotor helicopter and to the tilt-rotor. The joint heavy lift rotorcraft systems studies in the USA considered Large Civil Compound configurations with one or two main rotors in tandem or coaxial in the case of the Advancing Blade Concept, with a pair of wings or not and with different kinds of auxiliary propulsion. Another example is the kind of "competition" towards high speed between the Sikorsky X2, the Piasecki X-49A and the Eurocopter X3.

The old never ending Icare's dream of enabling each person to fly is another example of application between many others making rise alternate concepts. Last but not least, in recent years there are more and more studies for reduction of the pollutions associated with the aircraft operations (e.g. Cleansky – Green Rotorcraft). The EADS R&D project for hybrid power generation for helicopters (with its eCO2avia program) is an illustration of that vein.

After presenting the context and needs for this project, the paper will give a brief state-of-the-art in the field of methods for the pre-sizing and evaluation of rotorcraft.

Then it will address more deeply the approach for building such a tool. Three milestones have been defined:

1. setting up the modules and their workflows in the case of an existing helicopter,

2. setting up the models and methods in the case of a new helicopter to be optimized,

3. generalising the platform to alternate concepts and apply it for an innovative concept.

The global approach and the status of first developments will be presented. Year 1 (2011) is dedicated to the first milestone. Some first concrete results will be given regarding:

- Databases (rotorcraft and engines),
- Statistical/analytical models,
- Diagrams of dependences,
- Power balance assessment,
- Engine weight first presizing step.

Brief state-of-the-art

In this section of the paper, a brief survey of the related methods and tools will be drawn up. By explaining the differences with the intended CREATION platform that will also contribute to better define its purposes and features.

Of course there are as many predesign tools as industrial rotorcraft builders. These "house-tools" are generally based on databases of existing helicopters and make use of rather empirical methods. Such a pragmatic way is well suited for a quick and efficient presizing of a helicopter by interpolation within these databases, but not for the extrapolation of rotorcraft concepts different from the classical aircraft known by the industry. In the CREATION project the presizing is not a goal but rather a mean, in order to be able to evaluate any rotorcraft concept even when no or very few data are available. Such a capability will be built by putting the priority on the universality of the models by contrast with empirical laws and by taking into account as soon as possible in the predesign loops its multidisciplinary character and the associated complex optimization.

The scientific literature on the topic can be split into two main groups. First the abundant literature on the Multidisciplinary Design Optimization (MDO) methods presents a wide variety of possible formulations (e.g. [1]). Up to now their applications in aeronautics have mainly concerned fixed wings aircraft [2].

A second group of references deals with rotorcraft. They are themselves of two kinds:

- either rather "upstream" by comparison of our objectives in the meaning that they study mainly the methods for preliminary design (MDO formulations [3] or probabilistic approach [4]) but with models which seem to be below the level of expertise intended in CREATION ;
- or rather "downstream" by being focused on the study of a few concepts in the context of a precise flight performance objective ("joint heavy lift rotorcraft systems" [5] and "High speed rotorcraft" [6] studies).

The too seldom works the closest to the CREATION project are indicated hereafter.

<u>In Europe</u>:

At present none multidisciplinary rotorcraft dedicated platform is available in the European research establishments.

The NLR has developed a tool for the presizing but limited to helicopters : SPEAR "SPEcification Analysis of Rotorcraft". It does not have the same vocation as CREATION for the evaluation of alternate concepts with respect to helicopters. It rests on rather simple analytical models based on statistics and energy method. In the context of the EU project VIVACE (« Value Improvement through a Virtual

Aeronautical Collaborative Enterprise », Integrated Project in the European 6th Framework Programme), a model created by Eurocopter for estimating the « Life Cycle Cost » (LCC) of a helicopter was integrated into SPEAR. The goal was to get a tool allowing optimizing the predesign of a multi mission helicopter by minimizing its LCC [7].

Collaboration has been settled between ONERA and DLR on this topic from the beginning of the proposal. In their RIDE project (« Rotorcraft Integrated Design and Evaluation »), the DLR develops a rotorcraft evaluation platform following a similar multidisciplinary approach as already applied for fixed wings aircraft in their TIVA project (« Technology Integration for the Virtual Aircraft »). Two independent tools are developed with exchanges on some aspects and a mutual validation process between ONERA and DLR.

<u>In the USA</u>:
Besides the already mentioned works of the « Georgia Institute of Technology » on the methods for the preliminary design of rotorcraft, it must be indicated that a software tool was also developed to put them into practice: « CIRADS: Concept Independent Rotorcraft Analysis and Design Software » [8].

Recent papers have shown that NASA has developed a tool similar to CREATION called NDARC: « NASA Design and Analysis of Rotorcraft » presented by Wayne Johnson in January 2010 (e.g. [9]-[10]).

The role of this tool is both to sustain the research and the expertises in particular for the « Department of Defence » (DoD). The research activities find in that kind of preliminary design tool a mean for evaluation of the impact of a new concept or a new technology by integrating it in a complete adapted rotorcraft system. The support to the expertises during acquisition studies of new rotorcraft by the DoD concerns the exploration of concepts, their selection and improvement. During these different phases of acquisition, it is required to be able to evaluate independently a large variety of rotorcraft concepts and designs.

These two purposes are also those of the CREATION project: support the innovation and the expertises of rotorcraft at ONERA.

<u>In the rest of the world</u>:
In particular the work of the Technion Israël Institute [11]-[12] is noticeable. A platform for the analysis of rotorcraft concepts has been built called: «RAPID/RaTE» for «Rotorcraft Analysis for Preliminary Design / Rand Technologies & Engineering». It makes use of different levels of modelling from simple analytical models based on statistical analysis on existing rotorcraft databases (helicopters in [11] and extended with other rotorcraft concepts mainly of UAV type in [12]), until more sophisticated models including for example flexible blade modelling.

At ONERA, numerous works on rotor optimization both on aero-acoustics and aero-elasticity have been performed (e.g. [13]-[14]-[15]). The preliminary conception of a whole aircraft by using MDO techniques has up until now been addressed on fixed wings (airplanes and missiles [2]). In the field of rotorcraft, some first studies were carried out for the European project CAPECON on civil applications of Uninhabited Aircraft Systems (UAS) (see [16]-[17]), as well as for some specific concepts for the industry and the French Ministry of Defence.

As reported in [18], these rotorcraft conceptual studies have emphasized the need for a multi-department collaboration in order to better address the multidisciplinary character of rotorcraft evaluation studies. That is why this federative project has been launched involving six research units spread in five ONERA departments with expertises in aerodynamics, flight dynamics, structures, acoustics, system conception and optimization.

<u>Global approach</u>

In this section the main phases and milestones of the project will be presented. Then the organisation and structure of the CREATION tool will be described.

The project is scheduled on four years from January 2011 until December 2014 in three main phases with some overlaps:

<u>Main phases and milestones</u>
Phase 1: <u>General specifications</u>
Methodology of the rotorcraft evaluation process: method for comparing performances (criteria, typical missions), constraints, …
Diagrams of dependencies between disciplines (Flowcharts),
Specifications for the pre-design tool.

Phase 2: <u>Building the evaluation platform</u>
Databases for modelling,
Models for each discipline at each step of the conceptual study,
MDO formulations and optimization techniques,
Integration within a same environment.

Phase 3: <u>Demonstration / Comparisons</u>
Databases for validation,
Generic concrete tests cases: definition of two missions profiles,
Applications to a helicopter and to an alternate innovative concept,
Improvements.

Three main milestones have been defined to plan a step by step progress:

1. setting up the modules and their workflows in the case of an existing helicopter,
2. setting up the models and methods in the case of a new helicopter to be optimized,
3. generalising the platform to alternate concepts and apply it for an innovative concept.

Now we are working both on phases 1 & 2 in parallel with the goal of achieving the milestone 1 by the end of the first year. The existing helicopter considered for this first milestone is the Dauphin 365N for which most of the characteristics are known and a lot of flight test data are available at ONERA.

Organisation and structure

Up until now seven modules have been identified. Two are central within the tool, they can be called "purposes~aims modules":

- Flight performances,
- Environmental impacts (acoustics, air pollution, etc.).

Around this bipolar or "two hemispheres-brain-structure" of the tool, five "means modules" are "graviting" for providing the means for the flight performances and pollutions evaluations:

- Missions & Specifications
- Architecture & Geometry
- Weights & Structures (aerolasticity)
- Aerodynamics
- Power Generation (engine).

Within each of these modules there are models having different levels of fidelity/sophistication. In order to give a concrete image of the tool, it can be seen in a 3-Dimensional space as a building (see **Fig. 1**). The seven modules are its "seven funding pillars". A vertical structure is given by the multi-levels of modelling included in the tool. Three main modelling-levels are for the moment foreseen:

1. Level 0 ("ground level"): Power Balance and statistics (PB)
2. Level 1: Analytical Flight Mechanics (AFM)
3. Level 2: Numerical Flight Mechanics (NFM)

As can be seen in the names of these main levels, the main distinction comes from the Flight Performances modelling level which remains the central first goal of the tool. The Power Balance is the classical energy method in which the required power for making fly the rotorcraft is evaluated by decomposing it in different power terms as recalled hereafter. In this level 0 "PB", the other modules use statistical or analytical models. These reduced order models are based on databases which are the bottom-funding of this structure or they are deduced from simulation by the upper level models.

The level 1 "Analytical Flight Mechanics (AFM)" is named like that because at this stage the Flight Performances module uses analytical models even for the rotor which is of the rotor disk model type. The resulting forces and moments at the rotor hub centre are calculated by closed form expressions coming from the integration of the local blade forces distributions generally under an assumption of linear aerodynamics (the blade lift airfoil coefficient depends linearly on the local angle of attack). At this level 1, the comprehensive forces and moments transmitted by each of the main rotorcraft components (classically for a helicopter: main rotor, tail rotor, fuselage, horizontal and vertical stabilizers) are calculated by dedicated models. That is the difference with the PB level 0, and the Flight Mechanics levels 1 and 2.

The level 2 "Numerical Flight Mechanics (NFM)" distinguishes itself with the level 1 by using numerical blade element modelling for the rotor. Some other modules can also use numerical models at this stage (e.g. CFD, Computational Solid Mechanics).

So the tool is structured both with this horizontal organization in modules by discipline and with this vertical classification in modelling levels. Between them, diagrams of dependencies are established in order to organize the relationships and data-flows which can be both:

- vertical diagrams between the modelling levels, the lower levels aim at providing the data for the upper levels, that corresponds to the preliminary conception approach when the available data are incomplete for performing directly the rotorcraft evaluation with the highest modelling level ; reciprocally, the upper models can provide simulations or relationships which can be useful to derive and settle reduced models by different meta-modelling techniques ;
- horizontal diagrams within a same stage of modelling. They can be oriented "predesign" or rather "evaluation" some examples will be presented hereafter.

It can not be pretended to give at once all the diagrams of dependencies describing exhaustively all the possible workflows through the modules. That depends on the available data, models, specifications, type of rotorcraft, …

The first milestone does not really require optimization. For the next ones (2&3), a multicriteria approach will be implemented. Beyond the performances and environmental impacts criteria, the tool will be open to other aspects for example the "economical realism" of the concepts. An assessment in relative value is foreseen. Conception constraints imposed by the certification should also be taken into account.

A general 3-Dimensional view of the tool is shown on **Fig. 1**. The seven modules are present with a specific colour code. The three main modelling levels appear PB, AFM and NFM, with intermediate stages which can be required for enriching step by step the data needed for the next upper modelling level. The arrows are just for illustration of examples of horizontal diagrams of dependencies.

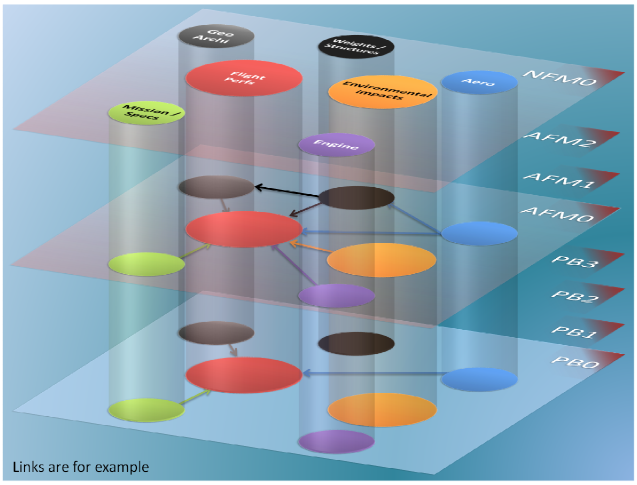

Fig. 1: a 3-Dimensional view of the CREATION tool.

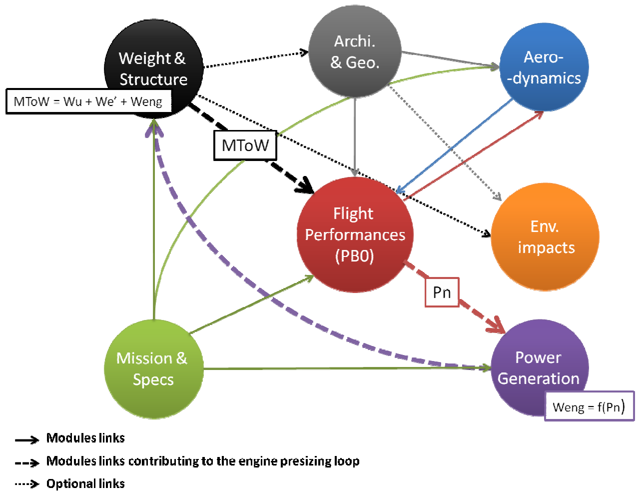

Fig. 2: engine weight first presizing diagram of dependencies.

Present Status of Development

Diagram of dependencies

A concrete example of diagram of dependencies is given on **Fig. 2**. That is the case of the engine pre-sizing. More precisely, a bi-turbine helicopter (single main rotor – single tail rotor, in practice the Dauphin 365N) is defined by all its characteristics except the engine. As a first exercise, the engine weight is determined by an iterative loop between the “Weights & Structures”, “Flight Performances” and “Power Generation” modules. The links corresponding to this loop are presented in dash lines on **Fig. 2**:

the “Weights & Structures” module calculates the take-off gross weight by summing the useful weight Wu, the empty weight (except the engines) We’, the engines weight:

$$TOW = Wu + We' + Wengs$$

With the useful weight fixed at its maximum value including the payload weight, the fuel weight, the crew and pax weight:

$$Wu = Wpayload + Wfuel + Wcrew\&pax$$

From the estimation of the Maximum Take-Off Weight (MTOW), the “Flight Performances” module calculates the required power Pn for this Hover Out of Ground Effect flight point (here at ISA sea-level).

From this required power, the “Power Generation” module estimates the weight of the engine able to provide the needed power including losses and accessory power.

This case of application (first presizing of the engine) will be illustrated later on. The dotted lines on **Fig. 2** indicate the extra data flows:

- between the “Weights & Structures” and “Architecture & Geometry” modules when the sizes of the helicopter are not fixed but estimated from the MTOW and empty weight ;
- toward the “Environmental impacts” module for the acoustic and air pollution calculation in HOGE.

Diagram of dependencies have also been established and put into practice with the present status of the tool for the evaluation of:

the power needed Pn at different flight conditions depending on the gross weight, speed, altitude temperature,

the characteristic speeds (for a given flight condition): maximum speed Vmax, best endurance speed Vbe, best range speed Vbr,

the optimum weight of fuel for a given mission profile,

…

Before presenting some examples of results, the status of the models implemented within the modules is presented hereafter.

Status of the modelling developments

The purpose of this paper is not to give a detail description of the models, but to provide a first general overview of the global approach and its present status of development.

As explained before and illustrated on **Fig. 1**, the tool has a multi-level modelling structure. Once again that is required for being able to assess the flight performances and environmental impacts of a rotorcraft concept whatever the data available for its description. Of course the validity of the evaluations depends both on the amount and quality of the data as well as on the degree of fidelity of the models.

Notice that a high fidelity model applied with some missing or poor estimates input data may provide poorer assessment compared with a simpler model well suited with respect to the data available.

So the idea is to build a tool which is able to make bottom-up evaluations from the lowest level of modelling adapted to the reliable data initially available until the highest modelling level required for the final expertise. That supposes to reconstruct step by step the missing data required by the higher levels through this bottom-up approach.

As mentioned before, during the first year the tool is built from the bottom level for a known helicopter. That allows using a top-down process for deriving some models of the lower modelling level from simulations by the higher models.

In its present status the models for the level 0 "Power Balance and statistics (PB)" have been settled and implemented within the CREATION tool. They are of two kinds:

- statistical models, obtained from databases of existing rotorcraft,
- analytical models, based on first principles and physics or deduced from simulations with higher level models.

Databases

Databases have been constituted on rotorcrafts, engines, noises, …

Today the rotorcraft database is made up of 219 rotary wings aircrafts: 173 helicopters, 9 coaxial, 8 tandems, 3 tilt-rotors, the rest is composed of Ultra-light Helicopters, Uninhabited Aircraft Systems, ... For each rotorcraft, data have been collected and put together in several groups:

- Main characteristics: MTOW, empty weight, number of rotors and their characteristics, type (main rotor, antitorque tail rotor, fenestron, tilt-rotor, etc.), diameter D, number of blades b, average chord C_{av}, revolution speed Nr, main dimensions (airframe length, height, width, overall length), number of crew, number of pax, …
- Engine: manufacturer, type, model, number, weight, Power take-off PTO, Maximum Continuous Power PMC, fuel type and capacity, …
- Performances: VNE (Never Exceed Velocity), Vmax, typical rate of climb, Ceilings (HOGE, HIGE, service), maximum range, maximum endurance, …
- General information: date of first flight, production status, certification codes, variants, …

Today the engine database is mainly composed of turbine engines and reciprocal-piston engines. For each engine the following characteristics have been collected (mainly from the Jane's journal, the Helicopter Annual of the HAI and information from the manufacturers):

- the weight
- the maximum continuous power
- the take-off power
- the fuel consumption
- the dimensions
- the certification date

These data are used in order to generate a statistical engine model which, for a given specific take-off power, allows to obtain (through iterations) an optimal engine minimizing the mass and specific fuel consumption.

The database is constantly evolving and some aspects linked to certification date (e.g. technological break-through) are under analysis.

Some models have been deduced from the analysis of these databases by using meta-modelling techniques. Up until now these surrogate models have been mainly generated by using statistical methods. Other approaches are under study (neural networks, etc.).

Architecture & Geometry

The level-0 A&G model has been derived from the rotorcraft database by statistical techniques similar to those presented for example in [11], [12] and [17]. That consists in multiple regression analysis estimating a probabilistic approximation relationship between one output Y and n input parameters X_i in the classical form:

$$Y = a.\prod_{i=1}^{n} X_i^{\alpha_i}$$

As shown in [11] and [12], most of the main dimensions of a helicopter are correlated through that kind of design trends with the MTOW. For example, the main rotor diameter D_{mr} and tail rotor D_{tr} (non fenestron) of a helicopter can be estimated by:

$$D_{mr} = 1.2244\,MTOW^{0.2792}$$

$$D_{tr} = 0.0871\,MTOW^{0.3966}$$

The length of the airframe L_{af} can be calculated by:

$$L_{af} = 0.9261\,MTOW^{0.3101}$$

These expressions are some examples of first rough approximations in the case of helicopters (single main rotor – single tail rotor) obtained from our database by statistics for the level 0 model. Other meta-modelling approaches are under investigation such as neural networks, …

Weights & Structures

At the level 0, the Flight Performances module uses a Power Balance (PB) modelling approach. Hence at this stage, a detailed weight breakdown is not required because the centre of gravity (cg) and inertia characteristics of the rotorcraft are not taken into account. They will be demanded at the Flight Mechanics levels 1 (AFM) and 2 (BFM).

Therefore three kinds of models are defined for the level-0 W&S module.

- The simplest one is reduced to the weight data: MTOW, empty weight, …
- The second one is a statistical model which is intended for giving a first estimate of the weight breakdown in order to contribute with the A&G module to the calculation of the cg

position and inertia matrix which will be needed from level 1 ;

- The third one (which is in preparation) is an analytical model in order to be sufficiently general and not limited to the kind of rotorcraft composing the database used for the generation the above model (second one). That will be useful for innovation about any concept requiring extrapolation with respect to the database of existing rotorcraft.

Flight Performances

The level 0 Flight Performances modelling is based on a classical Power Balance formulation also called energy method. The required power (P_{req}) to make the rotorcraft fly at a certain fly point is decomposed into different power terms. They are described hereafter in the case of a helicopter.

$$P_{req} = P_{reqMR} + P_{reqTR}$$

$$P_{reqMR} = P_{induced} + P_{blade} + P_{airframe}$$

➢ The induced power ($P_{induced}$) corresponds to the energy spent by the rotor to accelerate the air through its disk in order to develop a thrust mainly dedicated to the lift:

$$P_{induced} = T.V_{im}.\kappa_{mr}$$

At this level a rough induced velocity model is applied based on momentum theory:

$$V_{im} = \sqrt{\tfrac{1}{2}\sqrt{V^4 + 4V_{i0}^4} - V^2}$$

with V_{i0} the Froude mean induced air flow in HOGE:

$$V_{i0} = \sqrt{\frac{T}{2.\rho.\pi.R^2}}$$

This mean induced velocity through the rotor is then multiplied by a corrective coefficient K_{mr} for taking into account its non-uniformity on the rotor disk, the blade lift tip loss, …

In most of the flight mechanics applications, this coefficient is taken constant. Here a model has been developed within the Aerodynamics module (see further) for capturing its variations wrt. the thrust and the speed. The first version is mainly based on [19].

➢ The airfoil profile drag power (P_{blade}) : the blades generating not only lifting forces but also drag, the rotor spends a part of the power for countering the drag of its blades ;

$$P_{blade} = \frac{\rho \cdot R \cdot b \cdot c}{8} \cdot (\Omega.R)^3 \cdot Cx_b = \frac{\rho \cdot R^4 \cdot \Omega^3 \cdot b \cdot c}{8} \cdot Cx_b$$

$$Cx_b = \left(c_6 \cdot Czm^6 + c_2 Czm^2 + c_1 \cdot Czm + c_0\right) \times \left(1 + 5\mu^2\right)$$

$$Czm = \frac{K_{MR/F} \cdot 6 \cdot M \cdot g}{\rho \cdot R \cdot b \cdot c \cdot \Omega^2 \cdot R^2}$$

The profile drag coefficient Cx_b is here assessed by a first rough expression accounting for the mean blade lift coefficient C_{zm} and for the advance ratio μ.

$K_{MR/F}$ is a term for taking into account the download induced by the Main Rotor wake on the Fuselage. A more detailed interference model is also available which may be described in another paper. These terms are calculated by the Aerodynamics module.

➢ The anti-torque power (P_{reqTR}) : in the case of rotorcraft concept with anti-torque device as for the classical helicopter, a tail rotor spends a part of the power to develop a lateral force in order to compensate the main rotor torque due to the drag forces on its blades. At the level 0 a first rough approximation is to take proportional expressions wrt. the Main Rotor required power with a factor depending on the forward speed:

$$P_{reqTR} = k(V).P_{reqMR}$$

$$k(V) = \begin{Bmatrix} 0.1 & V \le 100 km/h \\ 0.02 & V \le 100 km/h \end{Bmatrix}$$

➢ The airframe drag power is the one for overcoming the drag of all the other elements except the blade airfoils (i.e. fuselage, empennage, rotor head, etc.) ($P_{airframe}$) : that is required in translation flight in order to overcome all the drag forces occurring with the translation speed.

$$P_{airframe} = 1/2.\rho.CxS_{af}.V^3$$

The equivalent drag area ($Cx.S_{af}$) is calculated by the Aerodynamics module.

Mission & Specifications

The specifications set the flight point: gross weight, pressure altitude, temperature, horizontal speed, rate of climb/descent, …

A sweep on one or more of these parameters can also be set in the output file of this module. A mission profile with several steps (take-off, hover, climb, cruse, descent, etc.) with the associated duration can also be specified e.g. for fuel consumption assessment.

Engines

The engine selection and the computation of its performance are mandatory during the design process of a rotorcraft. The engine model must be accurate and reliable to provide the correct trends and thus to allow the global optimisation process to choose the right engine design. In agreement with the global approach, three modelling levels are proposed for the engine.

Level 0 approach

This level deals with a statistical model based upon an engine database which collects for each engine, the power (MCP and TOP), the specific fuel consumption and the main characteristics (mass, main dimensions).

During the run of the process, the required TOP is provided as an entry in the database. Then, an

engine minimizing the SFC is chosen and the engine mass is provided. A new aircraft weight which includes the updated engine weight is computed, and the process iterates with a new required power. After convergence, the engine is chosen.
This very efficient process allows the user to simulate the entire mission if the performance map of the selected engine is known, which is usually not the case. The level 1 model will provide these information.

Level 1 model
The level 1 model aims at providing the performance map of an existing engine. In the particular case of the Dauphin 365N described here, the Arriel 1C (**Fig. 3**) must be simulated for all conditions of power, altitude and temperature.

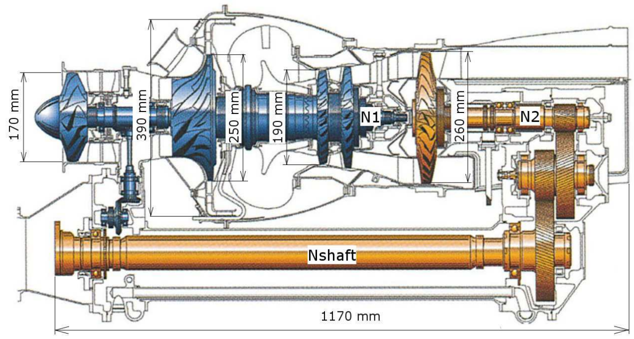

Fig. 3: Arriel 1C layout

The engine model simulates a thermodynamic cycle which includes a compression system made of an axial and a centrifugal compressor, a combustion chamber and two axial turbines (a two stages HP turbine and a free turbine). Then, the Overall Pressure Ratio (OPR), the components efficiency and the specific losses are tuned to match the data presented in Table 1 below. For simplicity reasons, the gas characteristics C_p and γ only have two values for cold and hot parts respectively. It is assumed that the Nozzle Guide Vane is choked and that gas is expanded to ambient pressure.

ARRIEL 1C	Pw	SFC	T45	N1	N2
	kW	kg/kW/h	℃	RPM	RPM
T/O	492		835		
MC	437	0.356(*)	785	50 505	44 733

Source : Janes, type certificate data sheet, (*)Estimated value
Table 1 – Arriel 1C main performances.

The thermodynamic cycle is calulated at various altitude, power and temperature (ISA) and leads to the performance map presented in **Figure 4**. As requested, this map provides the fuel flow over a large range of power and altitude, and at 3 ISA temperatures (-15, 0, +15). More, this graph provides the maximum power variations with altitude and temperature.

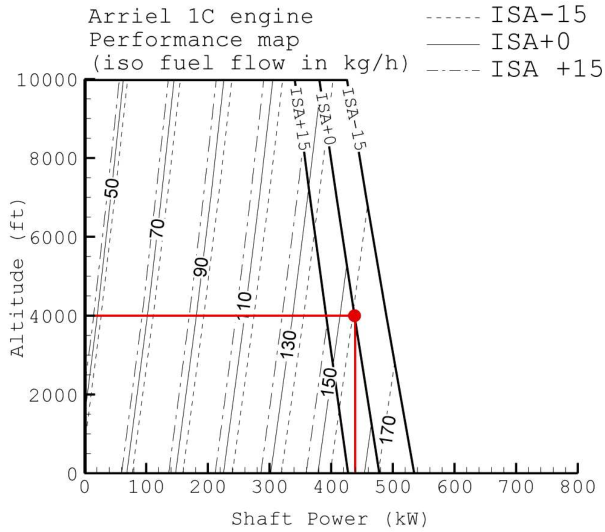

Fig. 4: Calculated Arriel 1C performance map

From these simulations an analytical meta-model (Response Surface Model) is deduced.

Level 2 model
This level deals with the design and the performance of an engine. The specification is the MCP for a given altitude/ISA, and the mission duration. The model outputs are all the main compressor features such as the architecture, the dimensions, and the engine weight. After this level 2 predesign phase, the compressor map is generated as described in the previous level 1 paragraph.
The predesign phase is based on the whole weight optimisation of the propulsion system, i.e. the engine plus its fuel for the mission. The engine weight is assessed by adding the weight of the compressor and of the turbine, which depends on the number of stages and the OPR chosen. Then, the SFC is computed and so the fuel quantity for the mission duration.
The engine model results (in red) for a two hours mission is compared to the database in **Figure 5** hereafter. The agreement is good both for SFC and engine weight. The steep SFC decrease at low power is mainly due to the variation of the component efficiency with dimensions, and so the OPR. The discontinuity observed around 1800 kW is due to the passage from two to three axial compressors.

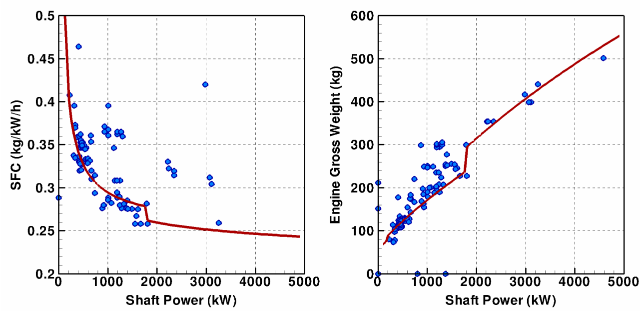

Fig. 5: SFC and gross weight v.s. shaft power.

Once the engine is designed, the performance map is generated with the same technique as described in level 1.

The environmental issues are taken into account by computing the CO2 emission with the equation:

$$CO_2 = 3.15 \cdot \dot{m}_c$$

In this equation, CO_2 is given in the same unit as $\dot{m}_c$ which represents the fuel mass flow, usually in kg/s.

The software only uses analytical formulations and only a few iteration processes. This tool is ultra fast and can be included in a higher level design tool as previously described.

Aerodynamics

The first level of the aerodynamic module (level 0) aims at evaluating by means of simple analytical formula the aerodynamic performance of the rotorcraft such as the induced power factor κ_{mr}, the mean drag coefficient Cx_b of the main rotor and the airframe drag coefficient $(CxS)_{af}$.

Fuselage

As indicated above, an aerodynamic model of the fuselage traditionally has to account not only for the fuselage but also the rotor head and pylon, the engine fairing and the tail surfaces. Two simple analytical models giving the surface drag area of the whole fuselage were developed, both based on a geometrical definition of the airframe.

For the simplest model of the fuselage, only the global dimensions of the helicopter are required. The friction drag is then defined using a cylinder of circular base representing the whole airframe. A mean friction drag coefficient over the fuselage is computed using Prandtl-Schlichting formula corrected for compressibility effects by Spalding and Chi approach, which provides the friction drag by multiplying by the wet area. The global fuselage drag is then obtained using a correlation proposed by Hoerner [20] relating total and friction drag for a streamlined body, function of the aspect ratio of the body. If a doghouse is present in the fuselage definition, it is taken into account by adding a base drag component. This base drag was estimated by Hoerner [20] as an empirical function of the upstream friction drag. Finally, the rotor head is considered as a percentage of the total fuselage drag.

The second model tries to go more in details into the description of the fuselage geometry. It is split into a set of elementary elements: main fuselage body, tail boom, engine fairings, pylon and hub, empennage and fin. Each element is represented by a simple shape (cylinder or cone, either with a rectangular or a circular base, for the fuselage, tail boom, fairings and pylon) for which the friction drag can easily be computed using the above procedure. The other main drag component, called viscous-pressure drag, comes from the thick wakes shed downstream the fuselage. They are mainly created by the boundary layer developing on the fuselage surface and across which a momentum deficit occurs. This component is computed using the same base drag approach described above using the differences in cross-section area between the various components of the fuselage. This allows accounting for an eventual doghouse as well. For the rotor head, an interaction effect, accounting for the high velocities in this part of the fuselage, as well as a correction due to geometric imperfections are also applied. Finally, the tail surfaces: empennage and fin, also create induced drag which is computed by a simple analytic formula also given by Hoerner [20].

Rotor

The level 0 rotor aerodynamic model consists on calculating the induced power factor κ_{mr} and the profile power mean drag coefficient Cx_b as a function of the blade mean lift coefficient *Czm* and the advanced ratio *μ*.

Following the approach of W. Johnson,[9][10][19] the induced power factor is first expressed, in hover condition, as function of the lift coefficient *Czm*:

$$\kappa_{hover} = \min(\kappa_{\min}, \kappa_0 + k_{h1}\Delta h + k_{h2}\Delta h^2)$$

with: $\Delta h = Czm - Czm_0$.

The coefficients of the model κ_{min}, κ_0, k_{h1}, k_{h2} and Czm_0 are set in order to follow the κ_{mr} evolution obtained by means of the HOST comprehensive code [21] for a reference rotor. As illustrated in **Fig. 6**, a simple linear function of κ_{mr} is sufficient to reproduce efficiently these HOST results (k_{h2}=0).

Then, considering forward flight, the induced power factor is expressed as a function of the advanced ratio:

$$\kappa = \kappa_{hover} + k_{e1}\mu + S_e\left(k_{e2}\mu^2 + h_{e3}\mu^{4.5}\right)$$

The constants k_{e1}, k_{e2} and k_{e3} are tuned in order to match the HOST results for *Czm=0.924*. For other lift coefficient values, the scaling factor *Se* is used to reach the same edge flight point: $\kappa_{mr}= \kappa_{edge}$ for $\mu=\mu_{edge}$ where κ_{edge}=*1.25* and κ_{edge}=0.2. As can be seen in **Fig. 7**, this first model gives a satisfactory agreement with HOST results except for combination of both very high thrust and very high speed.

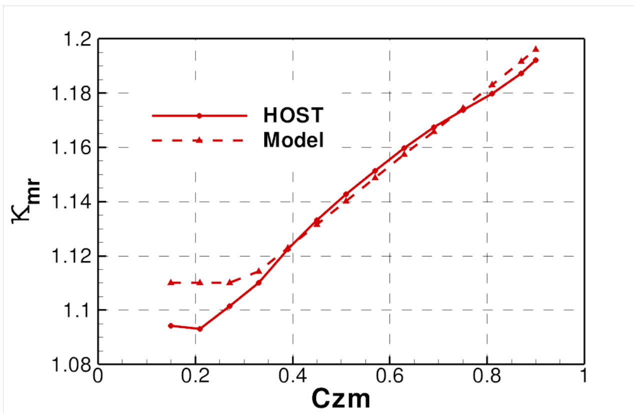

Fig. 6: Induced power factor as a function of thrust coefficient Czm for hover condition.

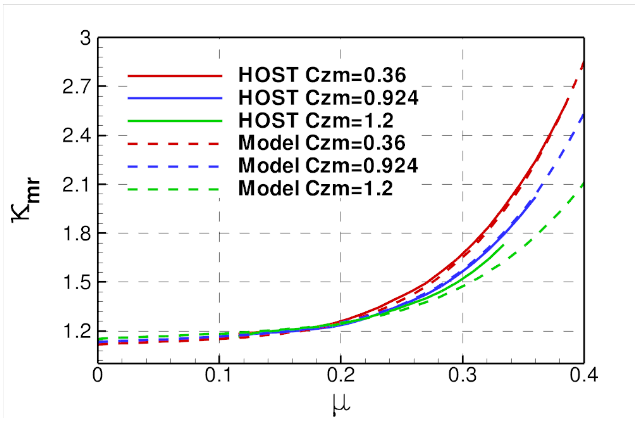

Fig. 7: Induced power factor as a function of advanced ratio and blade lift airload.

The evolution of the mean blade drag coefficient Cx_b in hover condition with respect to *Czm* is modeled by a sixth order polynomial in order to take into account drag rise at high thrust due to stall. As shown in **Fig. 8**, the Cx_b model curve matches quite well HOST results.
In order to take into account, the evolution of Cx_b with respect to the advanced ratio, the classical square law is here considered:

$$Cx_b = Cx_{b\,hover}\left(1+5\mu^2\right)$$

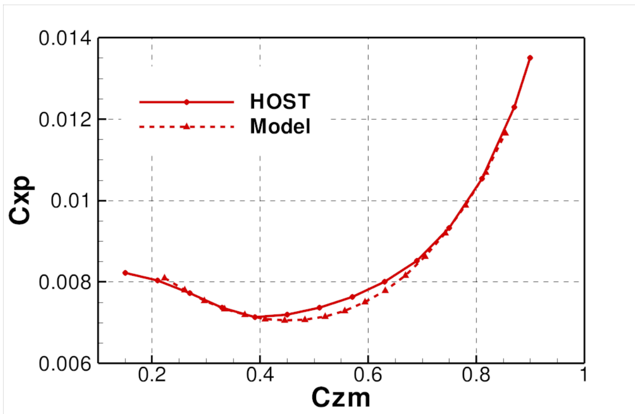

Fig. 8: Blade mean drag coefficient Cx_b as a function of mean lift coefficient Czm for hover condition.

Acoustics
As the other modules, the acoustic prediction is divided into different modelling levels.

The bottom level is a statistical model constructed thanks to a logarithmic regression on the CREATION database. Since this model is applied at early stage of development, only the helicopter gross weight (Gw) is considered as an available parameter. The result is an acoustic level in EPNdB and is given by a formula of the form:

$$EPNdB = A\log(Gw) + B$$

where the coefficient A and B depend on the flight conditions.

More refined acoustic predictions are very demanding in term of inputs. In order to reduce the amount of necessary data, an intermediate analytical level of modelling is based on a dimensional analysis of the Ffowcs-Williams and Hawkings (FWH) equation following the approach of Leverton [22]. The source term depends on the kind of noise considered (Blade Vortex Interaction (BVI), rotational noise, Fenestron, etc.). Finally, an acoustic factor is obtained allowing relative comparisons between rotorcraft. As an example, the Acoustic Factor (AF) for the BVI noise is given here after:

$$AF_{bvi} = \frac{Gw^2\Omega^2}{bR\left(1-M_r\right)^2}$$

with M_r, the rotational Mach number.

In order to obtain noise level predictions better contributing to the preliminary conception/evaluation of a rotorcraft, a more comprehensive analytical model is required. Main efforts have been made to compute the BVI noise considered as a major source of noise. In this case, the FWH equation in a compact source formulation is resolved (so that no discretization of the blade is necessary). Other sources of noise are considered using this technique like the tail rotor or the Fenestron (by ignoring the diffraction effect of the fuselage). When the source term is too complicated for being described analytically (mainly with the thin airfoil theory as in [23]), empirical models are used. That is the case for example of the compressor noise where the approach of Heidmann [24] has been retained. All the contributions are finally summed to provide the acoustic emission of the rotorcraft.

An important aspect of all these modelling developments is the consistency between the models. When put together within a calculation chain, the modules must be able to put in relationship models for which all the entries are available in the outputs of the other models as calculated or specified parameters.

Once consistent models are available for the “seven pillar modules”, they can be put together within a same integration environment.

Integration software environment
At least for the first year of the project it was decided to make the integration within a home-made environment called COLOSSE and within ModelCenter© in parallel. The idea behind is to check if the use of a commercial environment like ModelCenter© is mandatory. It may turns out that COLOSSE (for which all the sources are available and can be adapted to any requirement along the life of the project) could give satisfaction for the purposes of CREATION.

COLOSSE (which stands in French for « COnception Logicielle pour l'Optimisation de Systèmes Elaborés ») is a ONERA’s software written in TCL-TK. Any executable with ASCII input and output files can be integrated whatever its programming language (ForTran, C, C++, etc.). The DAKOTA toolkit [25] has been implemented within COLOSSE. It provides different optimization algorithms like the well-known gradient algorithm CONMIN.

Both COLOSSE and ModelCenter© are based on a graphical interface for connecting the different modules in an analysis map corresponding to a certain diagram of dependencies. Almost no coding is necessary neither in ModelCenter nor in COLOSSE where all is made with clicks and drag-and-drop operations. The compatibility of the workflows between the modules is automatically checked, i.e. the consistency between the inputs/outputs of the modules.

Of course thanks to its years of developments behind it, ModelCenter© beneficiates of functionalities which are not available for the moment in COLOSSE. Their actual interest for the project will be examined in practice during the building phase of the CREATION plateform as well as during the phase 3 "Demonstration / Comparisons".

An example of concrete translations of diagram of dependencies for the case of the first step of the engine presizing is shown on **Fig. 9** with COLOSSE and on **Fig. 10** with ModelCenter©.

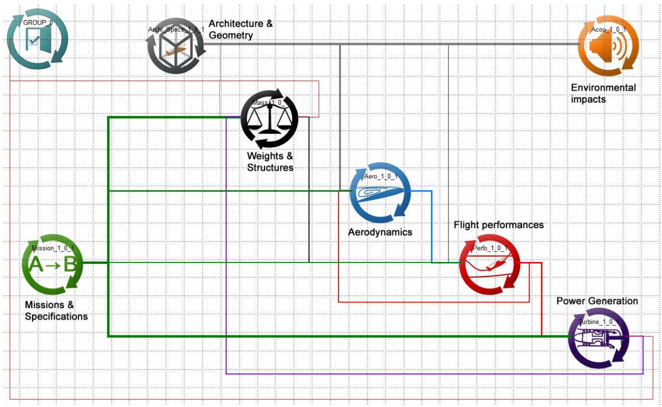

Fig. 9: example of diagram of dependencies within COLOSSE (first step of engine presizing).

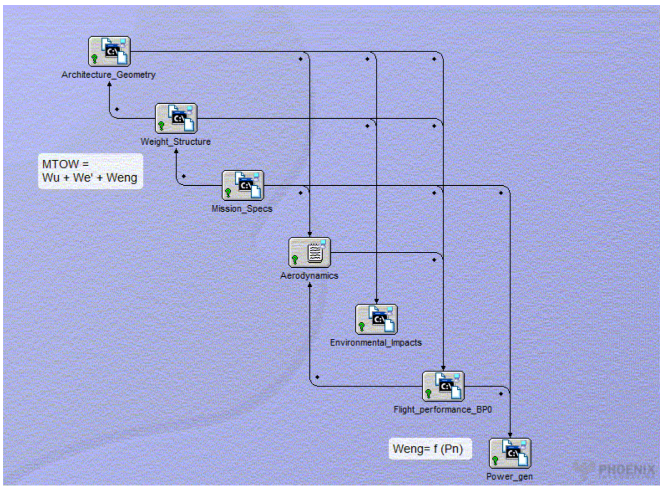

Fig. 10: example of diagram of dependencies within ModelCenter© (first step of engine presizing).

First example of results

The example of the first step of the engine presizing consists in assessing the weight of the engine able to provide the power required in HOGE at the MTOW (here at sea-level ISA as first exercise). In practice other aspects must obviously be considered for the engine presizing including other critical flight points in terms of ceilings, min/max temperatures, One Engine Inoperative, …

As sketched on the diagram of dependencies on **Fig. 2**, the "Weights and Structures" module estimates the MTOW. The "Flight Performances" module calculates the required power, then the engine module assess the weight of the engine able to provide the corresponding TOP accounting for the loss and accessory powers. This new engine weight assessment is then reintroduced in the "Weights and Structures" module for another iteration. In fact the crossing between two laws of dependencies is searched for:

- the power required wrt. the gross weight (here the MTOW) within the "Flight Performances" module,
- the power available wrt. the engine weight (here for the case of a bi-turbine engine helicopter).

At this level 0 of the modelling, this problem could probably be solved analytically because the level 0 engine model is a statistical design trend law and the PB0 model is a closed-form model. Yet it is worthwhile to set a numerical resolution since the same problem at level 1 and level 2 will be much more complex and even at level 0, more dependencies could be introduced for example by the "Architecture & Geometry" module as explained hereafter.

Therefore a fixed-point method has been implemented in order to assess this presizing point. On **Fig. 11** the results of the iterations are presented for two cases: when the initial engine weight is deliberately overestimated or underestimated. In both cases the calculations converge quickly toward:

- about 111kg in the case where the characteristics of the Dauphin 365N are specified in the "Architecture & Geometry" module ("specified 365N"),
- about 107 kg when the main dimensions (main rotor diameter, mean chord, etc.) are reconstructed wrt. the estimated MTOW by using a statistical model in the "Architecture & Geometry" module ("reconstructed 365N").

Both kinds of final results are close to the actual Arriel 1C engine equipping the Dauphin 365N (116 kg). The slight underestimation may be due to the fact that the actual engine presizing was done for design conditions more demanding than simply the HOGE at the MTOW in sea-level ISA condition.

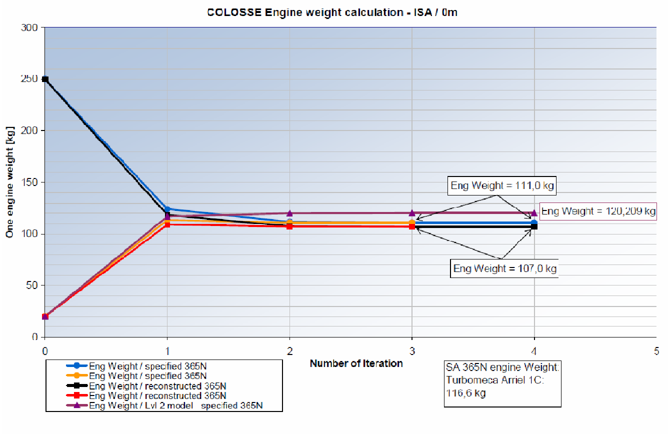

Fig. 11: convergence toward an engine weight first estimate in four cases.

A third kind of results is presented on **Fig. 11**: "Lvl 2 – specified 365N". It has been obtained with the level 2 engine model introducing a more detailed predesign of the turbine engine. Thus the SFC can be assessed and hence the criterion includes both the weight of the engine and the fuel weight (for typical mission duration). Notice that the engine weight estimation is in that case not estimated with the statistical design trend, but calculated by taking into account its components and sizes. The result (120kg) is in good agreement with the actual engine weight.

As soon as consistent models are available within the seven modules, other diagrams of dependencies can be settled for assessing for example: the characteristic speeds (Vmax, Vbe, Vbr), the ceilings and the resulting flight envelope. Instead of sweeping on the speed or on the altitude, these characteristics are determined in few iterations by using a gradient algorithm with DAKOTA toolkit.

Conclusions

The status of development of the CREATION project is presented as well as its motivations. It is clearly dedicated to the evaluation of innovative rotorcraft concepts. That supposes first to be able to evaluate more classical rotorcraft like the "single main rotor – single tail rotor" configuration. Three main levels of modelling have been defined. Up until now, the first level "Power Balance and Statistics" has been dealt with. Seven modules have been defined with consistent models inside in terms of inputs/outputs and modelling level:

- Flight performances,
- Environmental impacts (acoustics, air pollution, etc.).
- Missions & Specifications
- Architecture & Geometry
- Weights & Structures
- Aerodynamics
- Power Generation (engine).

A first practical application is presented corresponding to a first assessment of the engine weight.

Milestone 1 is dedicated to the expertise capability of existing/given helicopters. The next steps will be to build up the tool for the next modelling levels: Analytical Flight Mechanics, Numerical Flight Mechanics. Then the tool will have to be developed and exrended for addressing milestone 2 (evaluation of a helicopter to be conceived: predesign capability) and milestone 3 (enriching the models and methods for the evaluation of innovative concepts: "innovation capability").

Acknowledgements

The authors thank the ONERA Scientific Directorate for the funding in this study.

References

[1] J. Clément, N. Bartoli, J. Hermetz: "*Multi-disciplinary optimization methods studies*", *1st* EUropean Conference for AeroSpace Sciences, EUCASS 2007.

[2] C. Blondeau, G. Carrier, S. Defoort, J. Hermetz, P. Schmollgruber, "Toward multi-level, multi-fidelity, multi-disciplinary optimization at Onera", RTO MP AVT 173 Workshop on "Virtual Prototyping of Affordable Military Vehicles Using Advanced MDO", Sofia, Bulgaria, 16th to 20th May 2011.

[3] Adeel Syed Khalid: "*Development and implementation of rotorcraft preliminary design methodology using multidisciplinary design optimization*", Ph.D. Thesis, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, December 2006.

[4] Yongchang Li, Daniel DeLaurentis, Dimitri Marvis: *"Advanced rotorcraft concept development and selection using a probabilistic methodology"*, Aerospace Systems Design Laboratory, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, AIAA's 3rd Annual Aviation Technology, Integration, and Operations (ATIO) Tech, 17 - 19 November 2003, Denver, Colorado.

[5] W. Johnson, G. Yamauchi, M. Watts, *"Designs and Technology Requirements for Civil Heavy Lift Rotorcraft"*, AHS Specialists Conference, San Francisco, January 2006.

[6] A.J. Rudell (Sikorsky), J.A. Macrino (US Army Lab), *"Advancing Blade Concept High Speed Development"*, 36th AHS Annual Forum, paper N°80-57, Washington, May 1980.

[7] J.-F. Boer, J. Stevens et al., *"Multi-role Helicopter Life Cycle Cost (LCC) Optimization: The Pre-Design Strategy"*, presented at the 33rd European Rotorcraft Forum, 11-13 September 2007, Kazan, Russia.

[8] J. Davis, *"Design methodology for developing concept independent rotorcraft analysis and*

design software", Master's thesis, Science in Aerospace Engineering, Georgia Institute of Technology, December 2007.

[9] W. Johnson: "NDARC « *NASA Design and Analysis of Rotorcraft: Theoretical Basis and Architecture* », American Helicopter Society Aeromechanics Specialists' Conference, San Francisco, CA, January 20-22, 2010.

[10] W. Johnson: "NDARC « *NASA Design and Analysis of Rotorcraft: Validation and Demonstration* », American Helicopter Society Aeromechanics Specialists' Conference, San Francisco, CA, January 20-22, 2010.

[11] O. Rand, V. Khromov: *"Helicopter sizing by statistics"*, presented at the American Helicopter Society 58th Annual Forum, Montreal, Canada, June 11-13, 2002.

[12] V. Khromov and O. Rand: « *Design trends for rotary-wing UAVs »*, Presented at the 25th International Congress of the Aeronautical Sciences, ICAS 2006.

[13] A. Le Pape, "Numerical aerodynamic optimization of helicopter rotors: multi-objective optimization in hover and forward flight conditions", 31st European Rotorcraft Forum, Florence, Italy, 13-15 September 2005.

[14] A. Dumont, A. Le Pape, J. Peter, S. Huberson, "Aerodynamic Shape Optimization of Hovering Rotors Using a Discrete Adjoint of the RANS Equations", 65th American Helicopter Society Forum, Gravepine (TX), USA, 27-29 May 2009.

[15] J. Prieur, W.R. Spettstoesser: *"ERATO : an ONERA-DLR cooperative programme on aeroacoustic rotor optimisation" ,* 25th European Rotorcraft Forum, Rome, September 14-16 1999.

[16] P.-M. Basset, J. Deslous: *"Performances Comparisons of Different Rotary Wing UAV Configurations",* 31st European Rotorcraft Forum, Florence, Italy, 13 - 15 September 2005.

[17] C. Sevin, P.-M. Basset, J.-F. Boer, G.-M. Saggiani, *"Operational and technical design aspects of future civil rotary wing UAVs"*, presented at the 31st European Rotorcraft Forum, Florence, Italy, September 13-15, 2005.

[18] P.-M. Basset, C. Barthomeuf, A. Guillé: *"Setting up methods and tools for flight performance evaluation of rotorcraft concepts",* 3rd EUropean Conference for AeroSpace Sciences, EUCASS 2009, Versailles, July 6-9 2009.

[19] Wayne Johnson: "NDARC: NASA Design and Analysis of Rotorcraft", NASA/TP–2009-215402, December 2009.

[20] S. F. Hoerner, *"Fluid Dynamic Drag"*, Gauthier-Villar, Paris, 1965.

[21] B. Benoit, A.-M. Dequin, K. Kampa, W. Grunhagen, P.-M. Basset, B. Gimonet, "*HOST: A general helicopter simulation tool for Germany and France*", American Helicopter Society, 56th Annual Forum, Virginia Beach, May 2000.

[22] J. W. Leverton*: "Helicopter noise-blade slap, Part 1: Review and Theoretical Study*", NASA CR-1221, 1968.

[23] L. T. Filotas: "*Vortex induced Helicopter Blade Loads and Noise"*, Journal of Sound and Vibration, 27(3), pp. 387–398, 1973.

[24] M. F. Heidmann: "*Interim Prediction Method for fan and compressor noise"*, NASA TM X-71763, 1979.

[25] Adams, B.M., Bohnhoff, W.J., Dalbey, K.R., Eddy, J.P., Eldred, M.S., Gay, D.M., Haskell, K., Hough, P.D., and Swiler, L.P., *"DAKOTA, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 5.0 User's Manual",* Sandia Technical Report SAND2010-2183, December 2009. Updated December 2010.