

Conceptual Design of Environmentally Friendly Rotorcraft – A Comparison of NASA and ONERA Approaches

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ABSTRACT

In 2011, a task was initiated under the US-French Project Agreement on rotorcraft studies to collaborate on design methodologies for environmentally friendly rotorcraft. This paper summarizes the efforts of that collaboration. The French and US aerospace agencies, ONERA and NASA, have their own software toolsets and approaches to rotorcraft design. The first step of this research effort was to understand how rotorcraft impact the environment, with the initial focus on air pollution. Second, similar baseline helicopters were developed for a passenger transport mission, using NASA and ONERA rotorcraft design software tools. Comparisons were made between the designs generated by the two tools. Finally, rotorcraft designs were generated targeting reduced environmental impact. The results show that a rotorcraft design that targets reduced environmental impact can be significantly different than one that targets traditional cost drivers, such as fuel burn and empty weight.

NOTATION

ATR	Average Temperature Response
CAMRAD	Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics
CREATION	Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network
FOCA	Swiss Federal Office of Civil Aviation
GHG	Greenhouse Gas
HOGE	Hover Out of Ground Effect
HOST	Helicopter Overall Simulation Tool
ISA	International Standard Atmosphere
LOSU	Level of Scientific Understanding
NDARC	NASA Design and Analysis of Rotorcraft
OEI	One Engine Inoperative
RF	Radiative Forcing
RSM	Response Surface Model
b	Number of blades
$c_{d\ mean}$	Mean blade drag coefficient
C_T/σ	Rotor thrust coefficient divided by solidity
L/D_e	Effective lift-to-drag ratio = weight * speed / power
R	Rotor radius
UP	Utopian Point
V_{br}	Speed for best range
W_{xxx}	Weight of component xxx
Z_{cr}	Cruise altitude
α	Rotor shaft angle of attack
κ_i	Induced power factor
μ	Advance ratio
μ_z	Axial advance ratio

INTRODUCTION

Because air pollution is becoming increasingly regulated in industrialized nations, new rotary-wing aircraft will need to be designed for minimal environmental impact. In Europe, total CO₂ emissions by airlines were capped in the year 2012, with other emissions likely to follow. No such regulation has been enacted in the US, but may be in the future. If aircraft operators are limited in the amount of emissions they can legally produce, they will require designs that are not only efficient in terms of traditional metrics, such as fuel burn and maintenance costs, but that are also environmentally friendly.

Direct emphasis on environmental performance, particularly from an air pollution standpoint, has been largely absent up to this point in rotorcraft design, but it has been implicit in the design of fuel-efficient engines. Worldwide, aviation accounts for approximately 5% of all anthropogenic sources of radiative forcing, a measure of the atmospheric effects of various pollutants (Ref. 1). If rotorcraft are to become a large part of the civil aviation fleet, they have the potential to make a substantial contribution to aviation's overall climate impact. There are multiple existing metrics that can be used to evaluate the effects of combustion emissions on the environment. Metrics specifically targeted at evaluating aircraft emissions are also becoming available.

Collaboration on a task named "Environmentally Friendly Rotorcraft Concepts" has been ongoing since September 2011 between ONERA, NASA, and the US Army Aeroflightdynamics Directorate under the US-French Project Agreement on rotorcraft studies. The purpose of this task was to introduce environmental metrics in the design and evaluation tools for rotorcraft concepts. This paper provides a summary of the work that has been accomplished under this France-US collaboration.

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One of the first steps was to survey available metrics for measuring the environmental impact of rotorcraft. The primary focus was on air pollution, but the issue of noise was also addressed. Second, comparisons were made between the rotorcraft design and analysis tools in use by both NASA and ONERA. Baseline helicopter designs were developed as a common starting point for developing environmentally friendly rotorcraft. Finally, alternative rotorcraft designs were developed to optimize both traditional cost metrics and environmental performance metrics. This paper includes comparisons of the rotorcraft design tools and methods used by NASA and ONERA as well as examples of the environmentally friendly rotorcraft concepts that can be generated.

BACKGROUND

Rotorcraft Environmental Impact

Designing rotorcraft while taking into account environmental impact from an emissions standpoint is a fairly new area of research, though the impacts of fixed-wing aircraft have been studied for decades. There is significant uncertainty in many of the metrics that can be used to evaluate the effects of emissions. Figure 1 shows the cause and effect chain linking aircraft emissions to atmospheric changes and ultimately societal impacts (Ref. 2). Effects near the top of the figure are relatively easy to quantify, but are difficult to link to costs in terms of social welfare and are thus not very useful for evaluating rotorcraft concepts. Effects near the bottom of the figure are much more difficult to accurately quantify, but are much more relevant from a political and social standpoint. Any metric that is used to evaluate new rotorcraft concepts should balance uncertainty with relevance as much as possible.

In addition to choosing metrics that are relevant to current or future public policy and that have acceptable levels of uncertainty, it may be desirable to use metrics that account for all relevant aircraft emissions, rather than a single species. Figure 2 shows the radiative forcing (RF) in the year 2000 for the primary emission species produced by aircraft (Ref. 3). RF is a measure of the amount of heat trapped in the atmosphere by a particular pollutant, and is expressed in terms of trapped energy per unit area. The level of scientific understanding (LOSU) for each emission species is shown in the right-most column.

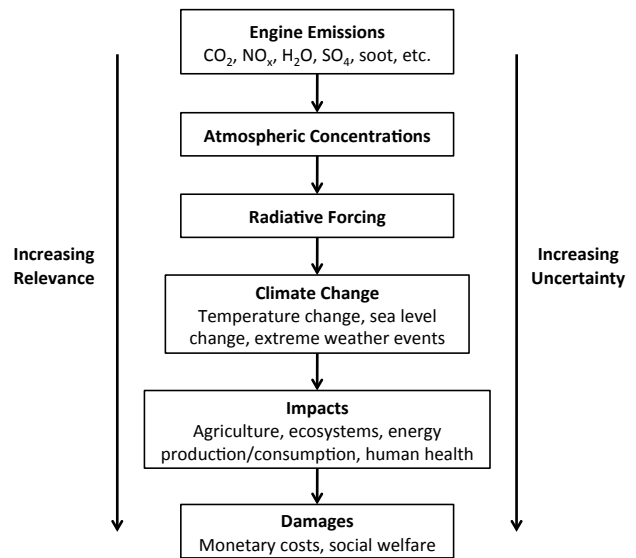


Figure 1. Cause-effect chain for climate change induced by aircraft emissions, adapted from Ref. 2

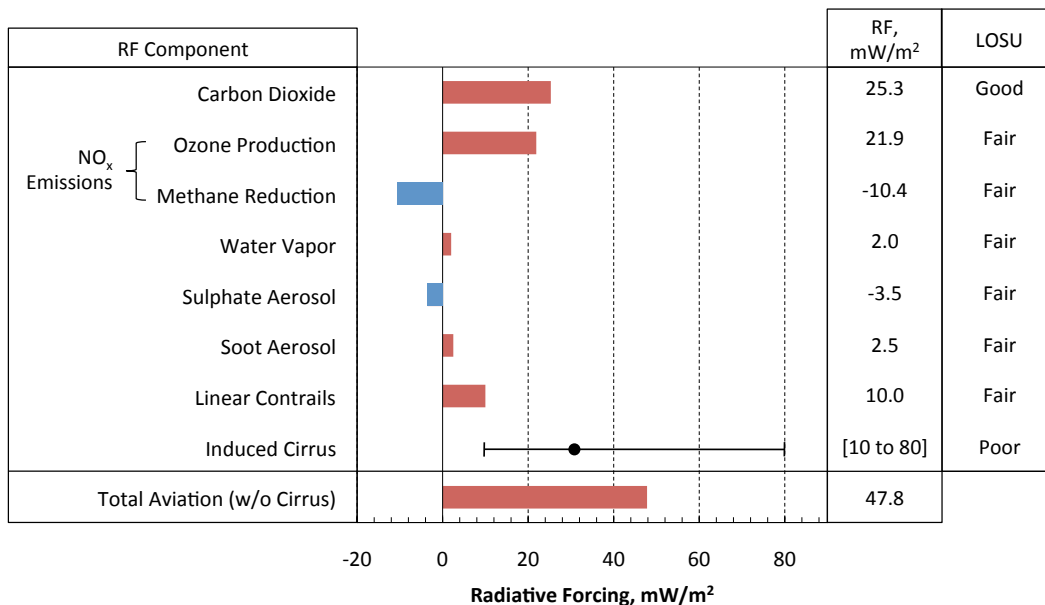


Figure 2. Components of RF due to various aircraft emission species, adapted from Ref. 3

NO_x emissions cause changes in RF indirectly through chemical processes in the atmosphere. Increases in NO_x lead to both increases in atmospheric ozone (a warming effect), and reductions in methane (a cooling effect) (Ref. 4). The methane reduction has a secondary effect of reducing ozone, so there are actually three components of RF due to NO_x emissions. Note that the impact of NO_x emissions is similar in magnitude to that of CO₂, but there is greater uncertainty in the NO_x RF values shown in Fig. 2. The black dot and error bars show, respectively, the best estimate and upper and lower bounds of RF due to induced cirrus reported in Ref. 3. The total RF due to aviation shown at the bottom of Fig. 2 does not include the effects of induced cirrus cloudiness, due to the low level of scientific understanding.

The contribution of rotorcraft operations to greenhouse gas (GHG) emissions is currently very low when compared with other sectors. Indeed, for the period 1970-2004, the transport sector contributed to 13.1% of the total anthropogenic GHG emissions (23% for just the year 2004). For the EU-27 (27 European Union Member States) in 2005, aviation represented 3% of the total GHG emissions. Helicopters represent only 1% of that, meaning they represent 0.03% of the total EU-27 GHG emissions and 0.36% of emissions in the transport category. Thus, in a global comparative assessment, current helicopter operations have a very small contribution, as illustrated in Fig.3 (reproduced from Ref. 5).

In Europe, after the “Friendcopter” project (2004-2008), which was aimed at reducing rotorcraft noise, a wider and more ambitious project was launched called “Clean Sky” (2008-2015). Targets were fixed for the entire environmental impact of aviation: reduction of GHG emissions (-26% to -40% of CO₂, -53% of NO_x), halving the perceived noise, and implementing a green life cycle (through the entire life of a helicopter, which is about 40 years). The ACARE (Advisory Council for Aeronautics Research in Europe) fixed even further reductions to be reached in 2020 with respect to 2000 levels: 50% reduction of CO₂ emissions, 80% reduction of NO_x and the same goal for the noise as in Clean Sky (-50% i.e. -3 dB of perceived noise).

Within Clean Sky, there are six “Integrated Technology Demonstrators” (ITDs) and a Technology Evaluator. One of the six ITDs is dedicated to rotorcraft and is called Green RotorCraft (GRC). A good recent overview of the GRC project was presented in Ref. 6. Further information relevant to the present topic is contained in Ref. 5, which also seems to be the first attempt to define a green metric specifically for helicopters.

Environmental Impact Metrics

Multiple metrics were considered to evaluate the environmental performance of rotorcraft. Two of the more promising metrics are described here. Ref. 5 focuses on CO₂ emissions, and it proposes a metric adapted for rotorcraft operations for quantifying their relative level of CO₂

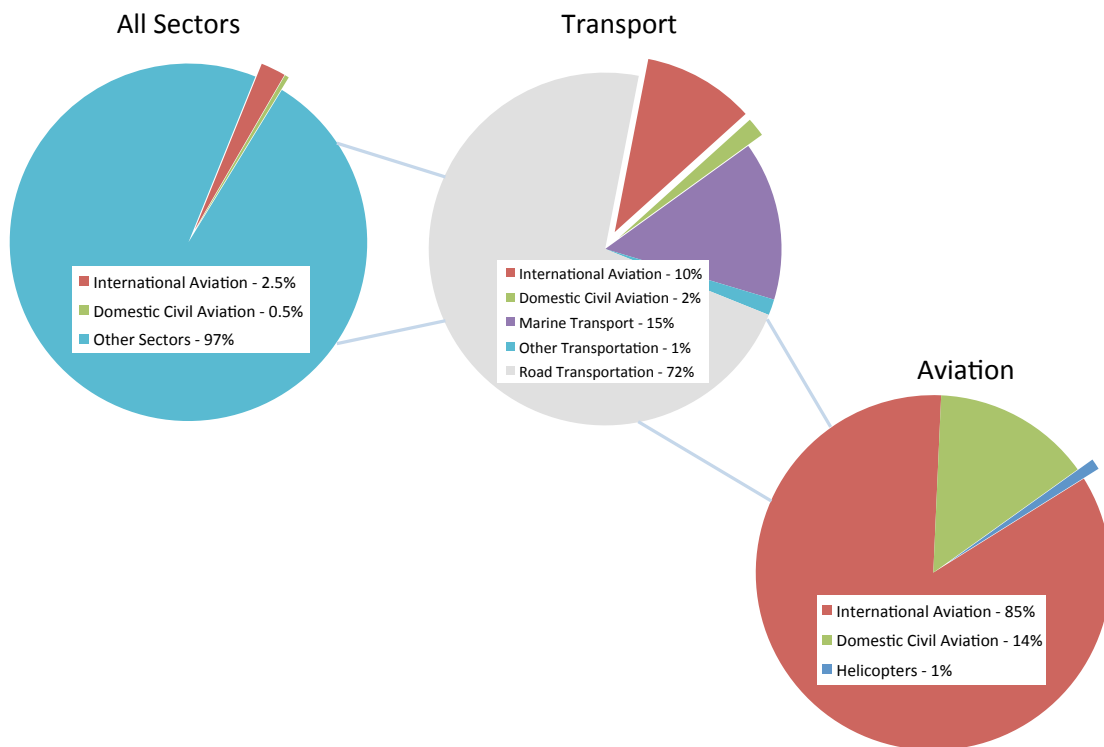


Figure 3. A European view of Helicopters’ GHG emission contributions in 2005 (Reproduced from Ref. 5)

pollution. One reason for this focus, despite the fact there are other kinds of GHG emissions by rotorcraft (e.g., NO_x, etc.) is that CO₂ emissions are directly proportional to the quantity of fuel burned. Indeed, if the combustion is considered as complete, these two quantities are connected by a simple stoichiometric relationship:

Quantity of CO₂ emitted \cong 3.16 x quantity of fuel burned

Therefore, all efforts for reducing the CO₂ emissions will be directly beneficial to the reduction of fuel consumption and, to a certain extent, the direct operating cost. The final proposed metric in Ref. 5 is the hourly fuel consumption divided by a certain quantity of “transported kilogram.” That allows the evaluation of the climate impact (in this case, the fuel burned) with respect to the service provided. It is proposed to use the useful load, which seems to be better adapted for rotorcraft than the passengers’ weight or the payload weight.

So the final proposed metric in Ref. 5 is:

Kilogram of fuel burned / hour / kilogram of useful load

determined at maximum takeoff weight Sea-Level ISA, by averaging the fuel consumption on a typical mission. This metric falls at the top of Fig. 1, since it is directly based on measurable quantities.

Another potential metric is the Average Temperature Response (ATR), a recently developed metric that specifically targets aircraft emissions. ATR uses measurable quantities as well as climate models to assess the relative performance of aircraft concepts with respect to climate change. The metric is measured in terms of global mean temperature change caused by operation of a particular aircraft. ATR can be used with a number of different climate models, but simple linear climate models are appropriate for the conceptual design of rotorcraft (Ref. 7).

The ATR metric is based on the radiative forcing generated by each emission species. Many climate change metrics, such as Global Warming Potentials, rely on RF, but do not specifically target emissions due to aviation (Ref. 8). The total RF for all emitted pollutants is used to calculate the global temperature response. The use of an altitude-sensitive climate model captures the effects of operating a particular aircraft at a multitude of operating conditions. In addition, ATR includes parameters such as usage rates and operating lifetime of the aircraft to determine the total climate impact that results from adding a particular aircraft to an operator’s fleet. For the current study, ATR was the primary metric used to evaluate rotorcraft environmental performance. It was also previously used in Ref. 9 to evaluate the environmental impact of tiltrotors.

Rotorcraft Software Toolsets

One of the goals of this collaborative research effort was to understand some of the differences between the rotorcraft conceptual design and analysis software tools under development at NASA and ONERA. This section gives a brief overview of the tools used by the two organizations.

Rotorcraft design software

The purpose of rotorcraft design software is to quickly evaluate rotorcraft concepts using reduced-order models that allow quick program execution. Both NASA and ONERA have been developing their own software codes for rotorcraft design over the past few years. These software tools are briefly describe here, and are extensively documented in external literature.

NDARC

NDARC (NASA Design and Analysis of Rotorcraft) is a conceptual/preliminary design and analysis code for rapidly sizing and conducting performance analysis of new rotorcraft concepts (Refs. 10-12). NDARC has a modular code base, facilitating its extension to new concepts and the implementation of new computational procedures. A typical NDARC run consists of a sizing task, which can be followed by off-design performance analysis. During the sizing process, mission performance is calculated and the aircraft is resized both geometrically and mechanically until convergence criteria are met. The software uses reduced-order performance models for various rotorcraft subsystems, such as rotors and engines, in order to facilitate short runtimes. These models require curve-fits to higher-fidelity models or experimental data in order to capture rotorcraft performance. Engines are represented using a non-dimensionalized model based on curve fits to real engine data. Mass flow is used to scale engine performance and size. For this study, CAMRAD II (Ref. 13) provided the rotor performance data for the NDARC model curve-fits. NDARC has previously been applied to environmentally friendly rotorcraft design in Ref. 9. Environmental impact effects were captured by post-processing NDARC output files.

CREATION

CREATION (Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network) is a computational workshop dedicated to the evaluation of rotorcraft concepts with respect to flight performance and environmental impact. It is composed of both models and methods tailored for rotorcraft presizing and evaluation. The models are distributed in seven disciplinary modules: flight performance, environmental impact, aerodynamics, weights and structures, power generation, missions and specifications, and architecture and geometry. Within each disciplinary module, several modeling levels are available in order to adapt the models used to the available data. Four main modeling levels are currently used:

- Level 0: Response Surface Models (RSM) based on databases or simulations
- Level 1: Simple analytical models based on physics
- Level 2: More comprehensive analytical models
- Level 3: Numerical models

More information can be found on the CREATION models in Refs. 14 and 15. The methods include both surrogate model generation techniques and Multidisciplinary Design Optimization (MDO) methodologies. An example of application of these different kinds of methods has been described in Ref. 16. Two different MDO approaches have been applied to the presizing of a 90-passenger helicopter in Ref. 17. One makes use of a genetic algorithm for computing first the Pareto front of the multi-objective sizing problem from a RSM of the modeling chain, and then a deterministic algorithm is applied for selecting a global optimal design. The other approach uses Mixture of Expert models for generating the RSM relative to each objective and then a deterministic algorithm for computing the best solution for each objective, and finally the global best compromise design. The general architecture of CREATION is given in Fig. 4, and a more thorough description of its use is contained in a later section.

Rotorcraft Comprehensive Analysis

NDARC and CREATION are both supplemented by rotorcraft comprehensive analysis codes to provide detailed rotor performance data used by the design codes' surrogate models. CAMRAD II is used to generate the surrogate models for NDARC, while HOST (Ref. 18) provides CREATION's rotor performance models.

CAMRAD II

For this study, induced and profile power calculated by CAMRAD II were used to calibrate the equations used by the NDARC rotor performance model. CAMRAD II is an aeromechanics analysis of rotorcraft that incorporates a combination of advanced technologies, including multibody dynamics, nonlinear finite elements, and rotorcraft aerodynamics. CAMRAD II finds the equilibrium solution for a steady state operating condition, and then produces the solution for performance, loads, and vibration. CAMRAD II has undergone extensive correlation of performance and loads measurements on rotorcraft (Refs. 19-26).

For this study, rotor performance analysis in CAMRAD II considered a single rotor for a tiltrotor or a conventional helicopter, but included both main rotors for a tandem design in order to capture interference effects. The calculations for calibration of the sizing code rotor model considered an isolated rotor, without interference from other components, such as the wing or fuselage. Rotor performance was calculated using free wake geometry for both hover and high-speed cruise. Airfoil characteristics were obtained from tables representing advanced technology airfoils. In hover, rotor thrust was varied from zero to above the point of stall. In cruise, the pitch, thrust, and forward velocity were varied through the expected envelope of operations.

HOST

HOST (Helicopter Overall Simulation Tool) is the Airbus Helicopters aeromechanics simulation code. ONERA has contributed to its development for years in many areas, such as rotor inflow and wake models, interference, and soft blade aeroelastic and dynamic stall models (e.g., Refs. 27-31).

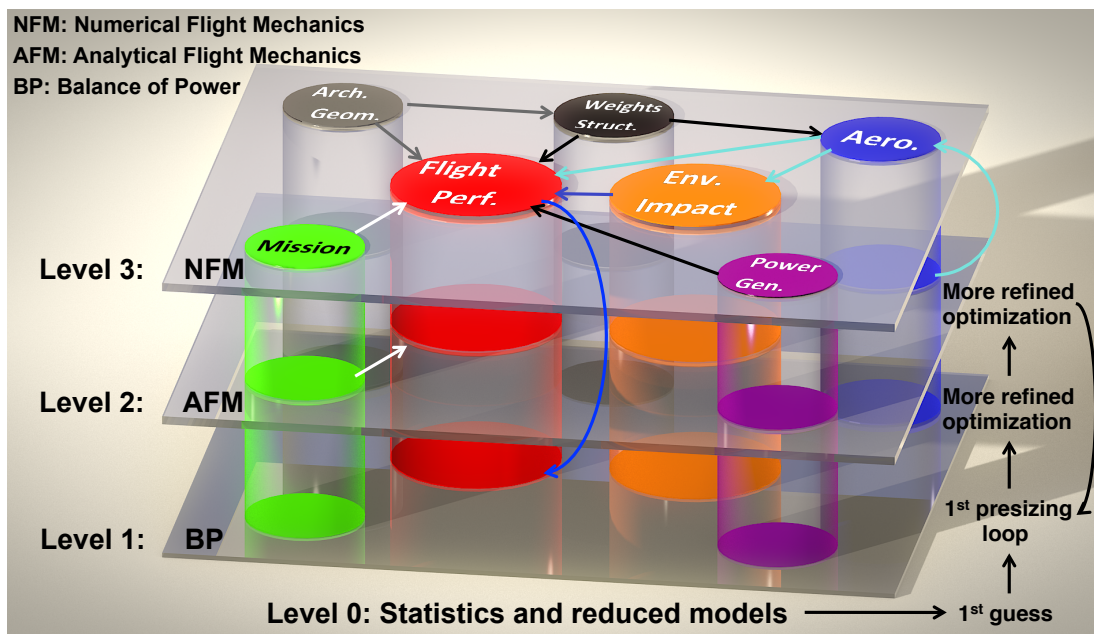


Figure 4. Organization of the CREATION tool

This simulation code is used both for detailed studies of rotor aeroelasticity (vibration and loads) and rotor aeroacoustics, as well as for the overall simulation of the rotorcraft flight dynamics. For years this code has been upgraded and validated with respect to wind tunnel test and flight test experimental databases for different kinds of helicopters and tilt-rotor configurations.

At the modeling Level 1 of CREATION, analytical aerodynamic rotor models are used for calculating the induced rotor inflow correction factor, κ_i , and the blade mean drag coefficient which are required for estimating respectively the induced power and the blade profile power. These analytical models are based on physics by including different terms corresponding to the different physical involved phenomena (e.g. stall, compressibility, etc.). They are calibrated with respect to numerical simulations performed with higher order aerodynamic rotor models. In practice at ONERA, these reference simulations can be done with HOST or FlightLab. Here the computations have been performed with the HOST blade element rotor model including soft blade aeroelasticity and a realistic aerodynamic field calculated by FiSuW (Ref. 32), the finite state rotor dynamic inflow model, truncated at the 24th order giving 325 states for a fine representation of the rotor inflow distribution.

Rotorcraft Designs

Three rotorcraft configurations were studied as part of this research effort: a conventional helicopter, a tandem compound helicopter, and a tiltrotor. All three aircraft were designed to fly a mission with a payload of 90 passengers (approximately 9,000 kg) over a distance of 1,000 km with additional reserve segments. The mission profile is shown in Fig. 5. Note that the cruise altitude was not specified, but was optimized as part of the design process. Cruise speed is also not specified, but rather optimized for minimum fuel burn. The design mission includes two reserve segments: one at cruise altitude for 185 km, and one at an altitude of 1,500 m for 30 min. Both reserve segments are flown at V_{br} , speed for best range. Two other sizing conditions are imposed. First, an OEI hover out of ground effect is required. Second the transmission is sized for maximum gross weight hover out of ground effect at maximum rated engine power under sea-level static conditions.

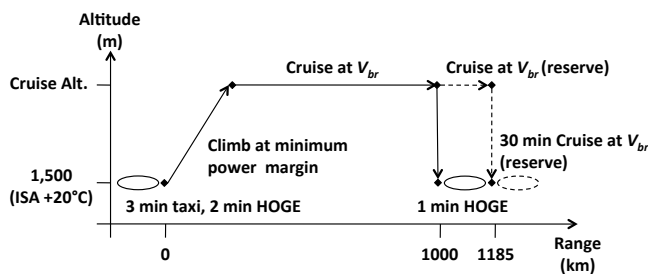


Figure 5. Design mission

The conventional helicopter design is shown in Fig. 6. This helicopter is designed to carry the 90-passenger payload over the design mission given in Fig. 5. The first iteration of this design was introduced in Ref. 33 as a baseline for comparison of tiltrotor and compound helicopter designs for a mission similar to the one shown above. The helicopter configuration was also used as a basis of comparison for the current study. The conventional helicopter was chosen as a baseline because it is a well-understood configuration, and was the first configuration that could be simultaneously modeled by both CREATION and NDARC.

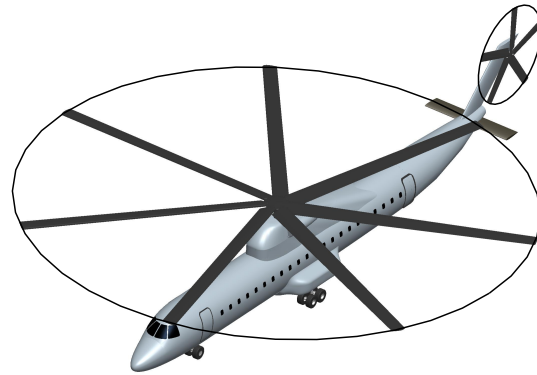


Figure 6. 90-passenger conventional helicopter configuration

The second rotorcraft configuration was a tandem compound helicopter, shown in Fig. 7. This compound helicopter configuration was chosen based on results from Ref. 34, which compared the performance of various compound helicopter configurations for a 500 nautical mile passenger transport mission. Of the four configurations studied (the other three being single-main-rotor aircraft), the tandem compound had the lowest fuel burn, empty weight, and installed power. There were two key reasons why the tandem compound outperformed the other designs: reduced download, due to the wing not being in the rotor downwash, and reduced disk loading, which was enabled by placing the two large rotors at the ends of the long fuselage.

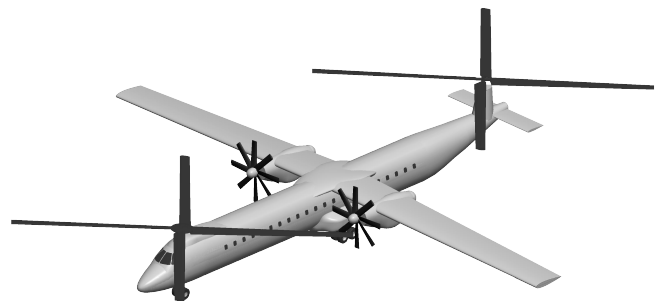


Figure 7. 90-passenger tandem compound helicopter

The third rotorcraft configuration studied was a tiltrotor. The tiltrotor modeled for this study was based on NASA's Large Civil Tiltrotor 2 (LCTR2), which has been extensively studied and refined over the past decade (Refs. 35 and 36). The 90-passenger tiltrotor configuration is shown in Fig. 8. The tiltrotor has previously been shown to perform better than either a compound helicopter or a lift-offset coaxial design in Ref. 37. One of the goals of the current study was to see how updated versions of the tiltrotor and tandem compound helicopters compare in terms of both conventional cost metrics and environmental performance metrics.

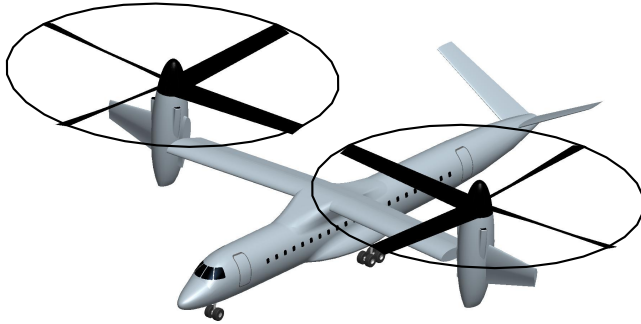


Figure 8. 90-passenger tiltrotor

There is a large amount of commonality between the three configurations. All three aircraft have the same fuselage dimensions. They also all have four engines, which are based on the same scalable engine model. Various fixed system weights, such as furnishings and hydraulic systems, are either equal or are based on equal scaling factors. All three designs also use a hover tip speed of 200 m/s. This choice of tip speed is based on predicted noise requirements for a passenger transport rotorcraft. A common set of technology assumptions are used. A technology factor of 0.79 was applied to all of the weight groups in NDARC. This weight-scaling factor was chosen to make NDARC and CREATION results for the baseline helicopter have approximately equal empty weights, allowing for a common starting point for the two software tools.

One difference between the helicopter and the compound and tiltrotor models was a difference in the transmission weight. Both the tiltrotor and the compound helicopter use a slowed rotor in cruise. Based on results from Ref. 38, a ten percent weight penalty was applied to the transmission to represent the shifting mechanism that is needed to slow the rotor. Another difference was the design C_T/σ . For the helicopter, C_T/σ was set to 0.09, based on typical values for helicopters. For the compound and tiltrotor configurations, a C_T/σ of 0.15 was used, based on results for maneuver requirements found by Ref. 39. Although there are some configuration-dependent differences between the designs, the goal was to use a common set of assumptions so that the benefits or limitations of the configuration would be clear in the final results.

DESIGN PROCESS

The underlying principles of the rotorcraft design processes at ONERA and NASA are very similar. Both organizations employ an iterative design process using reduced-order models that are supplemented by more advanced comprehensive analysis to calibrate various performance models. There are, however, a couple of key differences between the two tools.

With respect to vehicle optimization, CREATION employs a more formal optimization process, while the NDARC optimization process relies on manual variation of parameters. With respect to rotorcraft configurations, NDARC currently allows a more comprehensive suite of aircraft, including arbitrary combinations of components (i.e., wings, rotors, tails).

These differences reflect the focus of the software development for the two tools. Additional development is currently underway to add more formal optimization to the NDARC design process, and additional capabilities are being added to CREATION to model more arbitrary rotorcraft configurations. In the future, these additions will bring the capabilities of the two software tools more in line with one another. The following sections describe the design processes used by NASA and ONERA.

NASA Design Process

Much of the initial design for the three rotorcraft configurations described in the previous sections had already been completed in previous studies. Parameters such as number of blades, design C_T/σ , fuselage sizing, and tail volumes were therefore already pre-determined. For the current study, the main design variables investigated with NDARC were wing loading, disk loading, cruise altitude, and cruise speed. CAMRAD II was used to investigate main rotor tip speed in cruise, main rotor twist, and wing lift share in cruise. Designs were evaluated using empty weight, fuel burn, and installed engine power, as these three metrics tend to correlate well to cost. Environmental performance was evaluated using both total CO₂ emissions for the design mission (which are directly proportional to fuel burn) and the ATR metric. Noise was only addressed implicitly through the choice of hover tip speed.

The iterative design process used for this study is illustrated in Fig. 9. Tasks of the design process utilizing NDARC are contained in the heavier square boxes, while tasks using CAMRAD II are contained in the lighter rounded boxes. The rounded boxes with dashed lines indicate tasks that used a combination of CAMRAD II and spreadsheet analysis. Data passed between steps is identified next to the flowchart arrows. The process for each of the different configurations was generally the same, but certain steps only apply to one or two configurations. The steps in the process are outlined below.

1. Sweep aircraft parameters

Aircraft characteristics such as wing loading, disk loading, and cruise altitude were varied in NDARC using a baseline rotor model, resulting in an initial configuration.

2. Determine optimal lift share in cruise

The main rotor shaft angle was varied at fixed collective, and spreadsheet calculations were used to determine the lift share that provides maximum lift-to-drag ratio in cruise. The lift share step only applies to the compound helicopter.

3. Determine optimal cruise tip speed

To determine optimal tip speed in cruise, the rotor RPM was varied in CAMRAD II. The propulsive efficiency (for the tiltrotor) or the L/D_e (for the tandem compound) were used to evaluate cruise efficiency. The tip speed step does not apply to the conventional helicopter.

4. Analyze rotors with varied twist distributions

Using the rotor diameter and solidity determined in Step 1, rotors with varying blade twists were simulated in CAMRAD II at the design mission cruise and hover conditions to develop a set of candidate rotors.

5. Re-size aircraft for different twist distributions

The κ_i and $c_{d\ mean}$ determined in Step 4 for each of the candidate rotors were used in NDARC to re-size the aircraft. The rotor blade twist was chosen based on the candidate rotor that minimized fuel burn, empty weight, and engine power.

6. Generate updated rotor performance model

Using the rotor twist distribution determined in Step 5, various flight conditions were simulated in CAMRAD II to generate a math model of the rotor power consumption. While the κ_i and $c_{d\ mean}$ determined in Step 4 were for only two specific flight conditions, the performance model determined here spanned the expected range of operating conditions for the aircraft.

7. Re-sweep aircraft parameters

Using the rotor performance model generated in Step 6, aircraft characteristics were swept again to arrive at a revised configuration. Steps 1-6 could be repeated multiple times if necessary. For this study, the loop was only completed once for each aircraft.

8. Off-design analysis

Once the final aircraft design was determined, NDARC was used to analyze different operating conditions and missions. Post-processing tools were used to calculate environmental performance metrics.

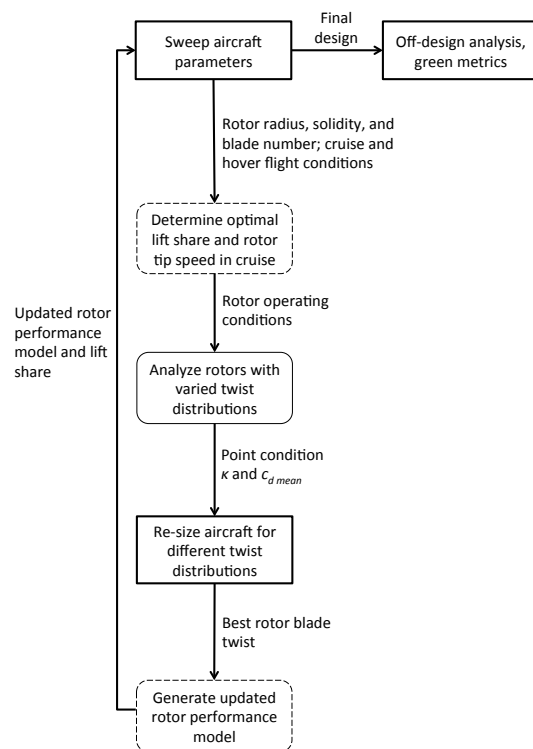


Figure 9. Iterative design process. NDARC tasks are in square boxes, and CAMRAD II tasks are in rounded boxes. Tasks using both CAMRAD II and spreadsheet analysis are contained in dashed rounded boxes

ONERA Design Process

The main components of the design process used by ONERA for this study include the following four steps:

1. Setting the Level 1 models of CREATION

The analytical Level 1 (see Fig. 4) rotor aerodynamic models for the considered rotorcraft concept are calibrated with respect to the available, “most up to date” rotor best suited for the studied configuration. In this study, for helicopter and compound designs, a rotor with the best up to date technology was simulated with HOST. For the tilt-rotor, a rotor based on the ADYN tilt-rotor (Ref. 40) was used as reference. From these simulations, the induced power factor and the blade mean drag coefficient analytical models are calibrated for the expected flight envelope (in terms of C_T/σ , μ and μ_e). The weight models are set up using statistics on databases for some parts and specific analytical models developed by ONERA for others (e.g., the blades, the wings, the fuselage, the main gear box).

2. Optimization process at Level 1

Two different methods for dealing with the optimization problem of multiple objectives under constraints for a rotorcraft predesign have been previously studied in Ref. 17 and are briefly described here. Results from both methods were applied to the current study.

Method 1: 2-step hybrid approach combining both a genetic algorithm and a deterministic algorithm

A) Multi-objective optimization with a Genetic Algorithm:
Allows global exploration of the design space giving a Pareto Front

B) Selection of a best compromise solution by a Deterministic Algorithm:

If the different objectives or cost functions are not of the same nature (e.g. weight, power, noise level, etc.), a normalization is required. From the Pareto front, the minimum and maximum values of each objective are known and thus their normalization is possible. For the case of objectives that will be minimized (which is the case of the objectives here):

$$\bar{F}_i(X) = \frac{F_i(X) - F_i^m}{F_i^M - F_i^m}$$

where X is a solution on the Pareto front P . The minimum and maximum values F of the objective i are given as:

$$F_i^m = \min_{x \in P} F_i(X) \quad \text{and} \quad F_i^M = \max_{x \in P} F_i(X)$$

By this way the solutions are non-dimensionalized to produce comparable values between 0 and 1.

Next, a global criterion is defined as being the distance with respect to the ‘‘Utopian Point’’ (UP), which represents the best values for each objective:

$$UP = (W_{fuel, min}, W_{empty, min}, F_{acou, min}, Obj_{i, min}, \dots)$$

W_{xxx} are various weights, and F_{acou} is a metric quantifying the noise level on the ground footprint during the landing approach. For this study, the objectives were minimum fuel burn, empty weight, and acoustic impact, in addition to maximum hover figure of merit and maximum cruise L/D_e .

A norm for quantifying the distance from the UP has to be chosen. Here, the Euclidean norm is used (with O the number of objectives):

$$\|\bar{F}(X)\|_2 = \sqrt{\sum_{i=1}^O \bar{F}_i(X)^2}$$

When the engineer has no preferences between the different objectives, an impartial global optimum can be assessed by calculating the solution on the Pareto Front that minimizes the distance with respect to the Utopian Point.

Method 2: Alternate approach using only a deterministic algorithm

With this method, the best solution for each objective is calculated with a deterministic algorithm (for example Nelder-Mead or Sequential Quadratic Programming). Once the best (minimum in this case) values are known, the Utopian Point is then defined. The global optimum can then be calculated as before by minimizing the distance with respect to the UP using again a deterministic algorithm to find the optimal design values.

This alternate method is quicker than the first one. However Method 1 is richer as it provides the Pareto front corresponding to the assessment of a wide range of optimal solutions. It should be emphasized that optimization processes often require the use of Response Surface Models instead of the complete chain of models. Method 1 is much more time consuming because a genetic algorithm for widely exploring the design space requires 10,000 to 20,000 computations of solutions. Therefore, Method 1 requires even more use of the RSM than Method 2.

3. Further predesign at upper modeling levels

Once the Level 1 optimization has provided a first assessment of the main design variables (e.g. for a helicopter, the main characteristics are the main rotor, the sizes of the fuselage and empennage, and the sizing of the engines), more refined optimization can be performed at upper levels. For example, a more detailed presizing of the tail surfaces requires the calculation of the equilibrium of the forces and moments at each flight point, which can be done from Level 2 using a flight mechanics model of the rotorcraft including interference from the main rotor wake. At modeling Level 3, a more detailed predesign of the blade can be studied by using a rotor blade element model allowing a more refined description of the blade geometric, aerodynamic, and structural properties: twist, chord, airfoil profiles, weights and stiffness, etc. The blade dynamics are computed in order to check that the eigenmodes are correctly placed. Iteration between blade aerodynamic optimization and blade dynamics assessment are performed until a well-suited blade definition is achieved.

From these more detailed optimizations, new simulations are generated for a better calibration of the analytical surrogate models used at Level 1. For example, for the rotor aerodynamics models, blade mean drag coefficient and induced power factor are tuned again to better reflect this more realistic (or more defined) rotor.

4. Repeat previous steps until solution converges

Another loop of optimization at Level 1 is repeated, followed by the other steps and so on until the whole definition of the rotorcraft is consistent through all the levels of modeling. For this study, Steps 1-4 were repeated at least two times.

COMPARISON OF SOFTWARE TOOL RESULTS

To ensure that NDARC and CREATION were providing similar results for a given rotorcraft design, comparisons were made between the software tools for the baseline 90-passenger helicopter and tiltrotor.

Comparing Comprehensive Analysis Codes

CAMRAD II and HOST are used to generate the surrogate rotor performance models for NDARC and CREATION, respectively. Comparisons were made between CAMRAD II and HOST results for the main rotor power of the 90-passenger helicopter as a function of speed. The results of these comparisons for free wake rotor simulations are shown in Fig. 10. Results are shown for profile (Ppro) and induced power (Pind) as well as the total power (Ptot). The two software tools generally produce good agreement on the required power.

Comprehensive analysis results were also compared for an example 90-passenger tiltrotor. For both the tiltrotor and the helicopter, the airframe forces and moments were calculated from polars that give six forces and moments as a function of angle of attack and sideslip angle for the major components (wing, fuselage, tails). The rotors were modeled with two different wake models in both CAMRAD II and HOST. The results for the components of power are shown in Figs. 11 and 12.

In Fig. 11, the CAMRAD II results are for uniform inflow. The HOST results are for Meijer-Drees inflow modeling. In Fig. 12, the CAMRAD II results are for free wake, and the HOST results use the FiSuW dynamic wake model. The agreement between HOST and CAMRAD II is generally good for both wake models. There is some disagreement in the total power at high speed, apparently due to differences in the calculated parasite power. This discrepancy appears to be due to a difference in trimmed pitch angle.

Comparing Rotorcraft Design Software Results

To ensure the engine models for NDARC and CREATION were producing similar results, comparisons were made between the two software tools for engine fuel flow. The engine here has a maximum rated power of 3,563 kW at sea-level-static conditions. The data generated in NDARC were for an engine scaled from the generic 4,000 HP (2,983 kW) engine model included with the distribution of the NDARC software. The results are shown in Fig. 13 for fuel flow at maximum rated power as a function of altitude for both hover and high-speed flight. As shown, the agreement is good between the two software tools.

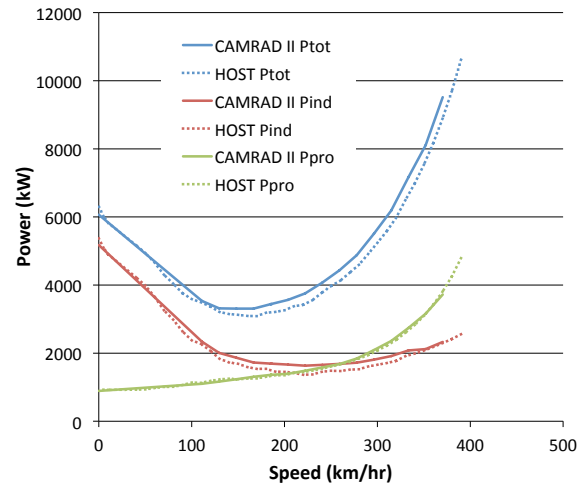


Figure 10. Comparison of CAMRAD II and HOST results for 90-passenger helicopter power consumption

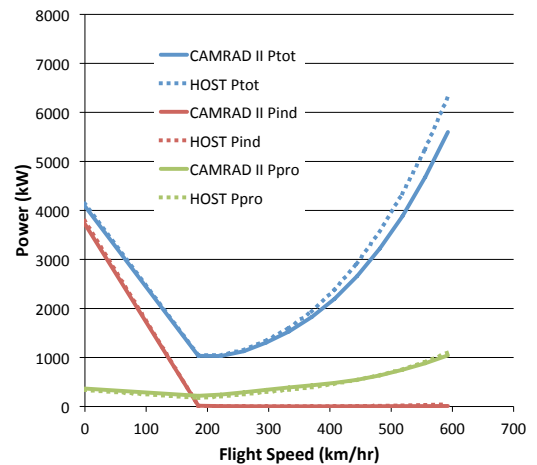


Figure 11. Comparison of CAMRAD II and HOST results for 90-passenger tiltrotor power consumption – simple inflow model

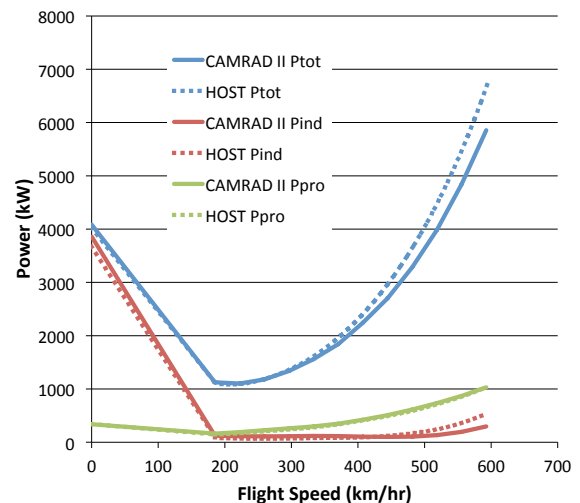


Figure 12. Comparison of CAMRAD II and HOST results for 90-passenger tiltrotor power consumption – detailed inflow model

Finally, similar 90-passenger helicopters were generated with both NDARC and CREATION to show whether the two design tools could produce comparable aircraft. Both software design tools were exercised to generate a 90-passenger helicopter for the mission specifications shown in Fig. 5. In NDARC, the assumptions on advanced technology (through the use of tech factors) were adjusted to match the empty weight of the NASA and ONERA designs. A universal tech factor of 0.79 produced good agreement on empty weight.

The bar chart in Fig. 14 shows weights of various component groups for the two resulting designs. The NDARC design is called H90, and the CREATION design is called HO-90. The empty weights of the two designs are nearly identical; however, some of the weight models used by NDARC and CREATION are quite different, so it is not surprising to see differences between the component weights. These differences are mostly small (less than 5%), but for the propulsion group, the difference is 22%, due to a difference in the transmission weights.

The radar plot in Fig. 15 shows a comparison of several design and flight performance characteristics of the H90 and HO-90 designs. The agreement between the two is generally good, except for hover ceiling, which is significantly higher for the CREATION design. The results shown provide confidence that NDARC and CREATION produce similar helicopter designs, allowing further exploration and optimization of green rotorcraft concepts.

ROTORCRAFT DESIGN RESULTS

With good agreement between NDARC and CREATION, the next step was to use the tools to optimize different rotorcraft configurations. For the initial designs, environmental performance was handled implicitly by targeting minimum fuel burn (and therefore minimum CO₂ emissions). The following sections describe the aircraft that were produced using this method. A later section describes the impact of applying the Average Temperature Response metric to the design process.

Helicopter

Results are presented here first for the NASA results and second for the ONERA results.

NASA Results

Some modifications were made to the NDARC model of the helicopter presented in Ref. 33. The scalable generic 4,000 HP engine model was used instead of the more advanced model used in Ref. 33, and the technology factor of 0.79 was applied across all weight groups. With the modified input parameters, disk loading and cruise altitude were varied to find optimal baseline values (step 1 in the design process previously outlined). A disk loading of 39 kg/m² and a cruise altitude of 3,700 m were chosen as the baseline values for the helicopter configuration.

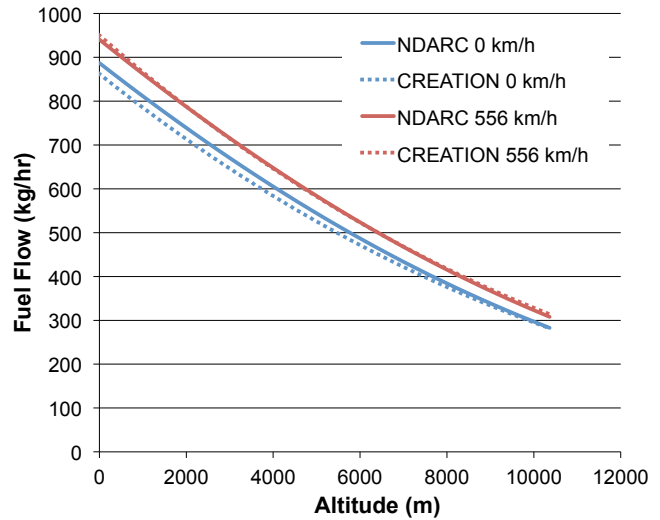


Figure 13. Comparison of NDARC and CREATION engine model results

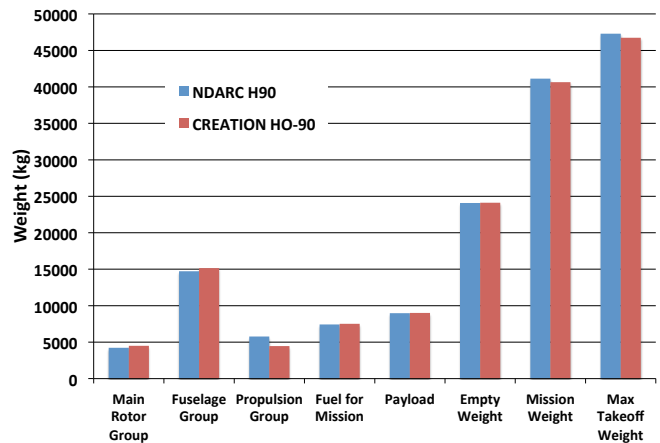


Figure 14. Comparison of 90-passenger helicopter design weights generated in NDARC and CREATION

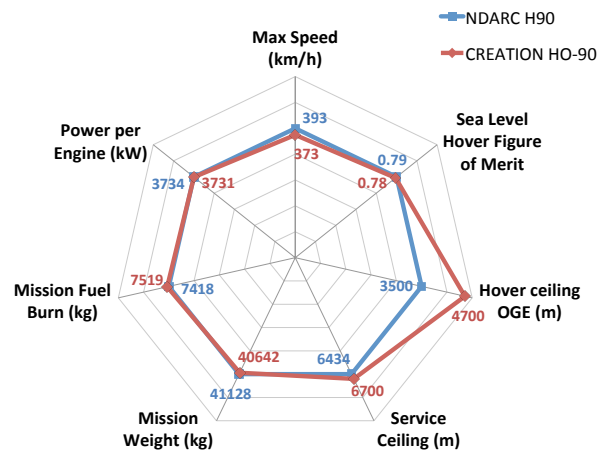


Figure 15. Comparison of 90-passenger helicopter design characteristics

With the baseline values for disk loading and cruise altitude chosen, the twist distribution of the main rotor was varied to achieve the best balance of hover and cruise performance. CAMRAD II was used to determine the performance of the main rotor for the two most important sizing conditions (Step 2 in the design process). These conditions are OEI hover, which sizes the engines, and the primary cruise segment, which sizes the fuel tank. The engine power is minimized by maximizing hover figure of merit, and the required fuel is minimized by maximizing lift-to-drag in cruise.

The CAMRAD II results form a Pareto front of cruise L/D_e vs. hover figure of merit along which the optimum twist must fall. Test points along the Pareto front were selected, and the corresponding induced and profile power factors, κ_i and $c_{d\,mean}$, were input into NDARC to find the twist that minimized fuel burn, engine power, and empty weight. The twist that minimized these values was -12 deg/R inboard and -14 deg/R outboard.

Once the rotor twist was chosen, rotor performance maps were generated by varying rotor thrust and speed in CAMRAD II. The coefficients of the NDARC rotor performance model were then tuned to match the CAMRAD II outputs. Finally, cruise altitude and disk loading of the helicopter were varied to determine their optimum values. Figure 16 shows the results for a sweep on altitude, and Fig. 17 shows the results for disk loading. A cruise altitude of 3,700 m provided the lowest fuel burn, empty weight and installed engine power. For the disk loading results, there is a minimum in empty weight at 44 kg/m², but fuel burn and engine power continue to decrease below the range of values tested. At low disk loadings, the blade aspect ratio gets very high. Based on values for helicopters currently flying, an upper limit of 20 was set on the aspect ratio of the main rotor blades. This leads to selecting a disk loading of 39 kg/m².

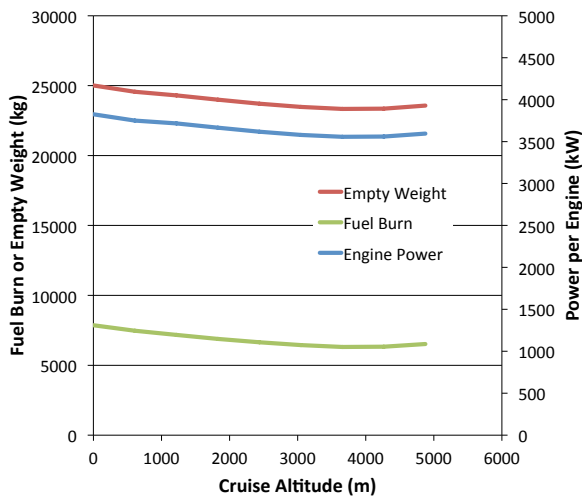


Figure 16. Effects of cruise altitude on the helicopter configuration; note that engine power is plotted on the secondary axis

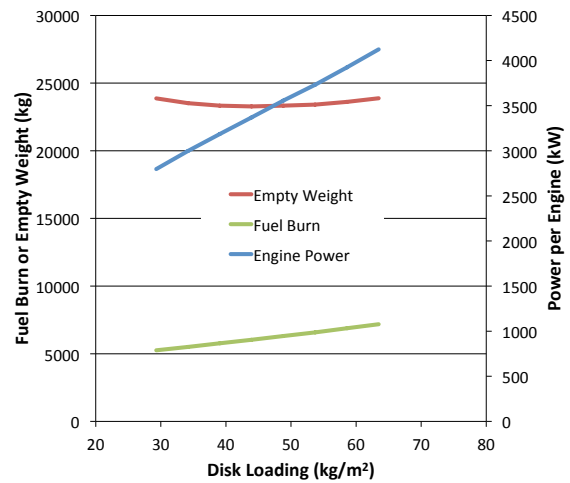


Figure 17. Effects of disk loading on the helicopter configuration; note that engine power is plotted on the secondary axis

ONERA Results

On the ONERA side, before switching to the predesign of other configurations, it was decided to work on further optimization of the HO-90 helicopter predesign. The goal was to refine the predesign by optimizing at the same time both the helicopter presizing parameters and the operational parameters (i.e. cruising speed and altitude). This work was performed in a study dealing with five incremental optimization steps considering operational parameters, helicopter design parameters, and engine presizing (with a fixed fuselage geometry for 90 passengers):

Step 1: Optimization of cruising speed and altitude, fixed helicopter and engine design (HO-90ini2)

Step 2: Step 1 plus engine predesign optimization

Step 3: Step 2 plus main rotor sizing optimization (radius, chord, number of blades)

Step 4: Step 3 plus main rotor rotational speeds (hover and cruise) optimization

Step 5: Step 4 plus alternate treatment of the OEI requirement

For the 5th step, the idea was to deal with the OEI condition differently as this requirement is very demanding (Hover OGE at 1,500 m ISA+20°C) and leads to engines that are over-sized for the design mission and therefore have increased fuel consumption. The engine presizing was done in Step 5 by considering four engines in hover, take-off and landing, but only three in cruise where the fourth one is in idle mode (a penalty of 5% extra fuel consumption was applied with respect to the fuel burned by the three other engines). The engine was presized such that it must be able to provide the takeoff power and minimize the fuel consumption in cruise.

Significant reductions of fuel burn on the whole mission and therefore of the emitted air pollutants have been obtained with respect to the initial predesign (HO-90ini2): ~19% with step 1, 19.5% with step 2, about 24% with step 3, about 26% with step 4, about 51% with step 5. These results are illustrated in Fig. 18.

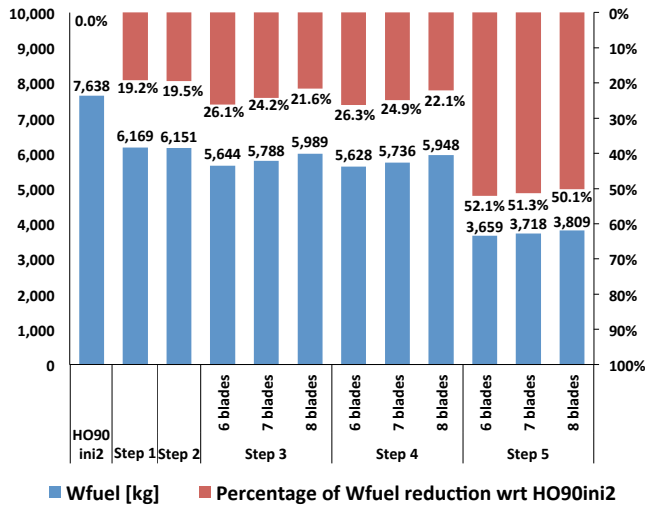


Figure 18. Reduction of fuel consumption with the 5 optimization steps with respect to the initial design (HO90ini2)

The cruise speed remains very close to the minimal imposed value (~280 km/h), regardless of the optimization case. The optimal cruise altitude (Z_{cr}) varies significantly for each optimization step and with the number of blades, b . For example:

$$\text{Step 3: } Z_{cr}(b=6) = 1,000 \text{ m ; } Z_{cr}(b=8) = 1,663 \text{ m}$$

$$\text{Step 4: } Z_{cr}(b=6) = 822 \text{ m ; } Z_{cr}(b=8) = 1,358 \text{ m}$$

$$\text{Step 5: } Z_{cr}(b=6) = 2,125 \text{ m ; } Z_{cr}(b=8) = 2,943 \text{ m}$$

In all of these cases, it is interesting to note that the optimum cruise altitude for the helicopter is lower for the ONERA results than for the NASA results.

The tiltrotor and compound helicopter configurations are still being studied on the ONERA side. At the time of this writing, however, their presizing is on going within the CREATION numerical workshop. NASA results are now presented for the compound helicopter and tiltrotor configurations.

Tandem Compound Helicopter

Starting with the tandem compound helicopter designed in Ref. 34, a uniform technology factor of 0.79 was applied across all weight groups, and the generic 4,000 HP NDARC engine model was implemented. Initial parameter sweeps led to a baseline design with a wing loading of 490 kg/m² and a

disk loading of 49 kg/m². Using the new tandem compound baseline design, main rotor tip speed and wing lift share were investigated simultaneously. To accomplish this task, the main rotors were simulated in CAMRAD II at a speed of 426 km/h, which is the optimum cruise speed determined by NDARC. Rotor collective was fixed at 0 degrees at 75% radius, which was shown by Ref. 34 to produce the best L/D_e for the tandem compound configuration. Rotor cyclic controls were used to trim the rotors to zero hub moment. Shaft angle of attack was varied for different values of tip speed, resulting in varied amounts of lift on the rotor. Spreadsheet analysis (described in further detail in Ref. 34) was then used to determine the L/D_e of the whole aircraft.

The results for main rotor tip speed and lift share are presented in Fig. 19. From the results shown, the optimum tip speed appears to be very low, below the range of values tested. In fact, lower tip speeds were run in CAMRAD II, and the results suggested that the L/D_e would continue to improve as tip speed was further decreased; however, those results were not well converged, so they are omitted here. Because there are additional structural and control considerations (not studied here) at high advance ratios, especially above 1.0, the tip speed was limited to 120 m/s. This tip speed gives an advance ratio just under 1.0. Figure 19 shows that the maximum L/D_e for this tip speed occurs at a shaft angle of attack of 3 degrees, giving a wing lift share of 93 percent. The rotors at this light loading and shaft angle have a very low power input of less than 100 kW.

The twist of the main rotors on the tandem compound was selected using a similar process to that for the helicopter. Of the twist values tested, an inboard twist of 9 deg/R and outboard twist of -18 deg/R gave the best results.

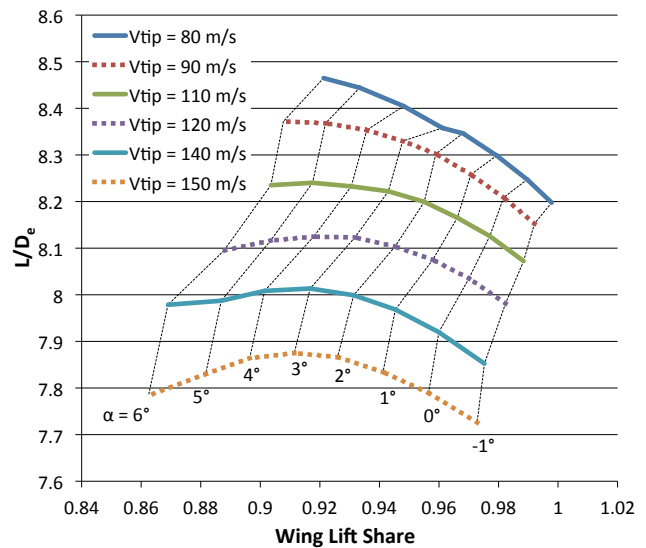


Figure 19. Effect of main rotor tip speed and wing lift share on tandem compound cruise efficiency

With the lift share and main rotor tip speed and twist determined, wing loading, disk loading, and cruise altitude were varied a second time to arrive at the final sized aircraft. The altitude results are shown in Fig. 20, followed by the wing loading and disk loading results in Figs. 21-23. The parameter sweeps show that a cruise altitude of 7,300 m minimizes engine power, fuel burn and empty weight. There is a sharp increase in all three metrics above 8,200 m. The reason for knee in the curve is that above this altitude, the cruise speed, which is speed for best range, V_{br} , is also the maximum speed for the installed power. The cruise segment therefore sizes the engines above 8,200 m, causing a more rapid rise in power and weights. Below this altitude, the OEI hover requirement sizes the engines.

A wing loading of 440 kg/m² was chosen as the best balance between minimizing fuel burn, empty weight, and installed power; fuel burn benefits from a slightly lower wing loading, and empty weight is minimized for a higher wing loading. Disk loading was set to 54 kg/m². A lower disk loading would be preferable to minimize power, fuel burn, and empty weight, but would result in the main rotors hitting the propellers.

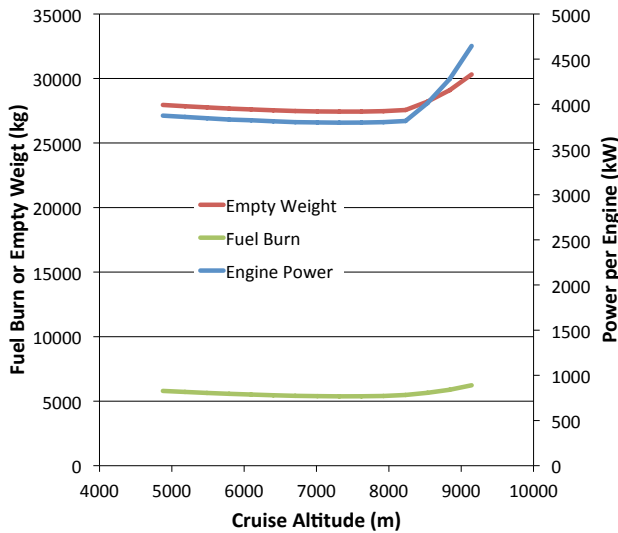


Figure 20. Effects of cruise altitude on the tandem compound configuration; note that engine power is plotted on the secondary axis

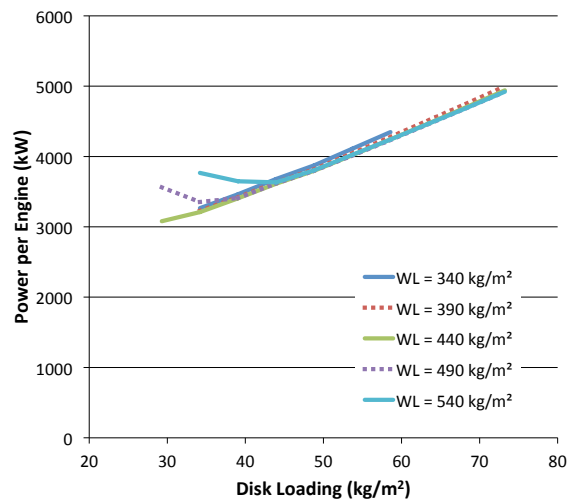


Figure 21. Tandem compound engine power as a function of wing loading and disk loading

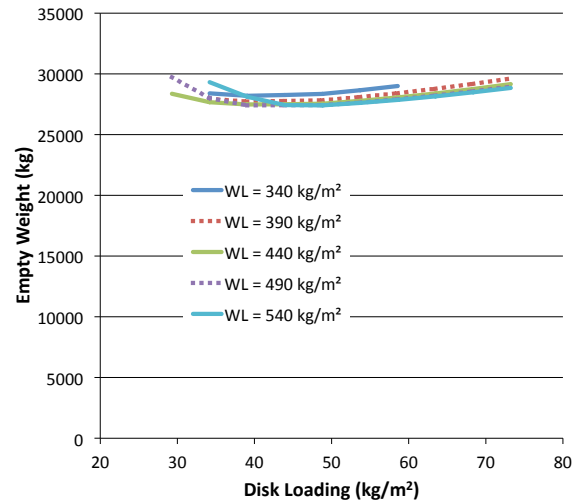


Figure 22. Tandem compound empty weight as a function of wing loading and disk loading

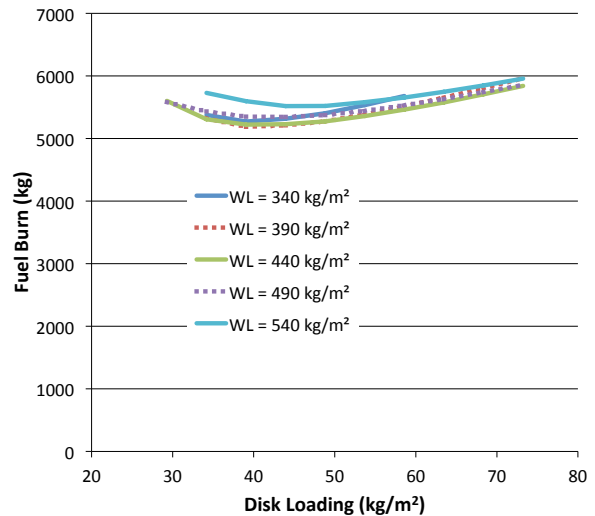


Figure 23. Tandem compound fuel burn as a function of wing loading and disk loading

Tiltrotor

As with the helicopter and tandem compound, the engine model for the tiltrotor was replaced with the scalable generic NDARC engine model, and a uniform technology factor of 0.79 was applied across all weight groups. Initial parameter sweeps led to a baseline disk loading of 68 kg/m^2 and a wing loading of 490 kg/m^2 . The first design parameter investigated was tip speed. CAMRAD II was used to simulate the baseline rotor in hover and cruise at 556 km/hr . The baseline tiltrotor design had a cruise tip speed of 120 m/s . To provide high cruise efficiency, the blade twist for the tiltrotor was the helical sweep angle of the blade in axial flight at a speed of 556 km/hr . A different twist distribution was therefore implemented for each tip speed. Figure 24 shows how rotor propulsive efficiency in cruise and figure of merit in hover differ for varying cruise tip speed (and therefore varying twist distribution). The hover cases all use a tip speed of 200 m/s . As Fig. 24 shows, hover performance favors a twist distribution for a slightly lower tip speed than cruise. A cruise tip speed of 110 m/s was chosen for the final design.

Performance maps of the rotor were generated in CAMRAD II for various flight conditions, and a second set of parameter sweeps on cruise altitude, wing loading, and disk loading were performed. Figure 25 shows the effects of cruise altitude on engine power, empty weight, and fuel burn. The cruise altitude that minimizes all three metrics is $10,400 \text{ m}$, but as Fig. 25 shows, there is a sharp rise in the engine power and weights above this altitude, similar to the knee in the curves for the compound helicopter, shown in Fig. 20. The cause of the sharp rise is the same in both cases: the cruise segment begins to size the engines above a certain altitude. To avoid generating designs that would land on this rise, a lower cruise altitude of $10,100 \text{ m}$ was chosen.

Wing loading and disk loading were varied using a cruise altitude of $10,100 \text{ m}$. Figures 26-28 show the effects of wing loading and disk loading on engine power, empty weight, and fuel burn. A wing loading of 440 kg/m^2 gives the best results. With this wing loading, engine power and fuel burn are minimized for a disk loading of 59 kg/m^2 , and empty weight is lowest for a disk loading of 78 kg/m^2 . For the final design, a disk loading of 68 kg/m^2 was chosen as a compromise between minimum empty weight and minimum installed power and fuel burn. One point to notice about the tiltrotor results is that the weights and power do not continue to decrease as disk loading decreases. The reason for this is that the wingspan is determined by the clearance of the rotors with the fuselage. For low disk loading at constant wing loading, the wing aspect ratio therefore becomes high, resulting in a very heavy wing. The minimum in the plots represents the best compromise between the effects of wing weight and the rotor's induced power in hover.

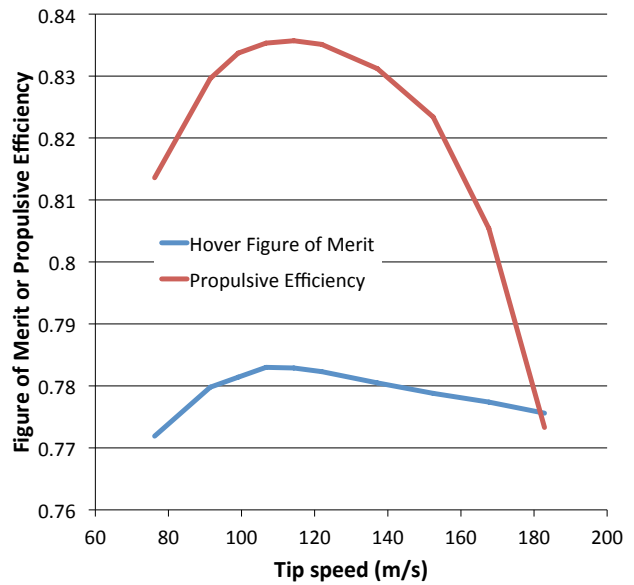


Figure 24. Tiltrotor figure of merit and propulsive efficiencies for varying cruise tip speed

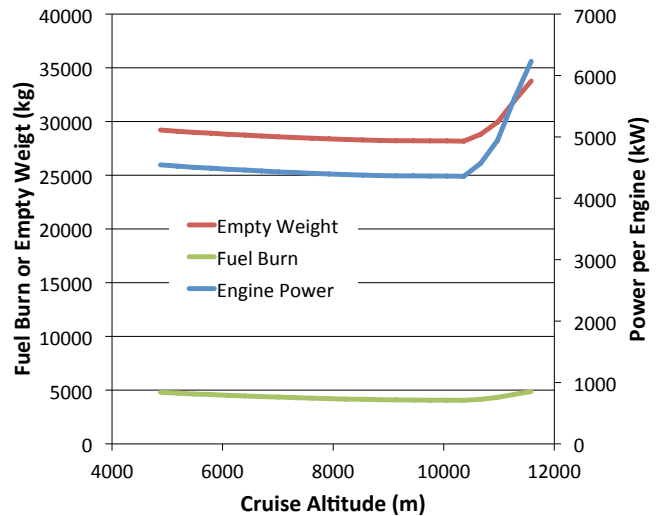


Figure 25. Effects of cruise altitude on the tiltrotor configuration; note that engine power is plotted on the secondary axis

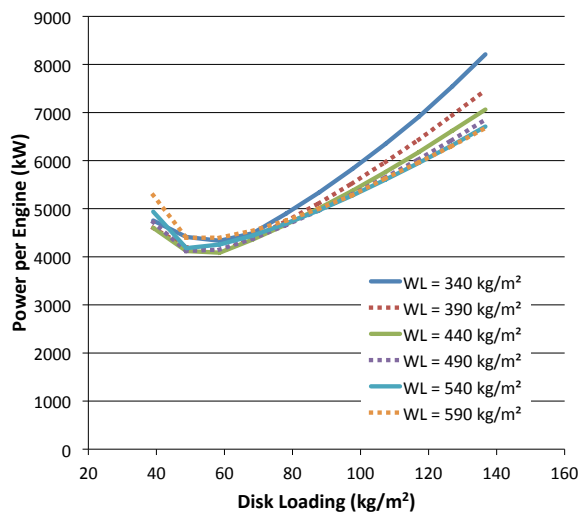


Figure 26. Tiltrotor engine power as a function of wing loading and disk loading

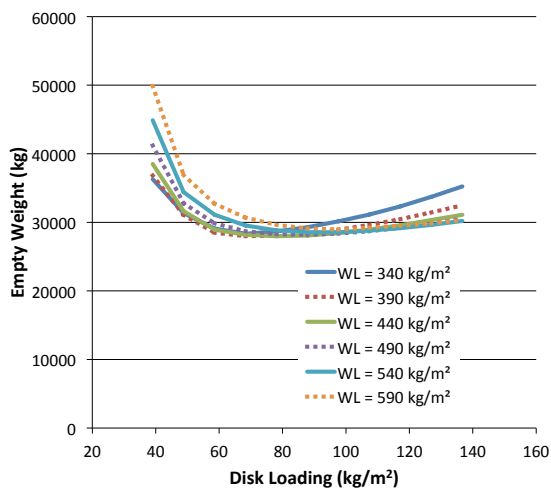


Figure 27. Tiltrotor empty weight as a function of wing loading and disk loading

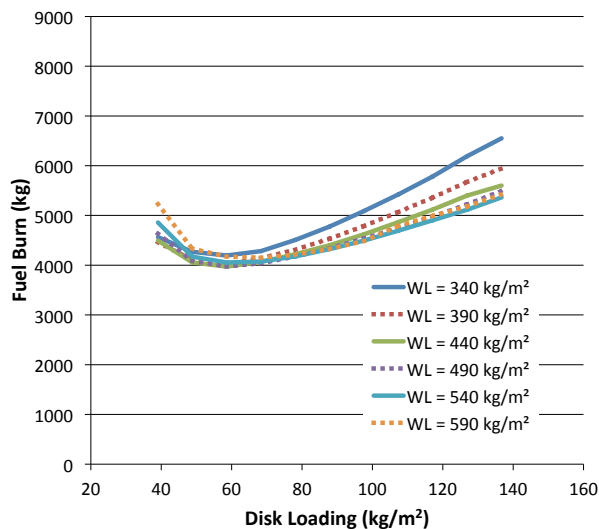


Figure 28. Tiltrotor fuel burn as a function of wing loading and disk loading

Environmental Performance Metrics

As previously noted, carbon dioxide emissions are generally independent of operating conditions, so they can be easily calculated by multiplying the fuel burn by a factor of 3.16. NO_x emissions are more challenging, as they depend on operating conditions as well as engine technology. While there is a large amount of published turbofan NO_x emissions data and established methods for estimating variation with altitude, much of the data for the turboshaft engines used by existing rotorcraft is proprietary. To the authors' knowledge, there is no publicly available data that quantifies NO_x emissions for specific turboshaft engines. There is a limited amount of data that has been collected by the Swiss Federal Office of Civil Aviation (FOCA) as part of their efforts to develop an emissions inventory for civil aviation, but this dataset has considerable uncertainty (Ref. 41). The FOCA methods and data have been used for some recent studies, such as Ref. 42, that seek to model helicopter NO_x emissions. They were also used by ONERA for the current study to calculate NO_x emissions. Another method based on published turbofan emissions data and the DLR fuel flow method (Ref. 43) was used in Ref. 9 and by NASA in the current study to estimate upper and lower bounds on tiltrotor NO_x emissions.

In order to calculate NO_x emissions with this method, a baseline engine must be chosen. The GE CF34-3B and the Honeywell HTF7000 have fuel flows similar to what is calculated in NDARC for a turboshaft engine. Both engines are relatively modern, high bypass ratio, small turbosfans. The HTF7000 and CF34 also represent the upper and lower bounds on NO_x emissions for this category of engine, so they should bracket the expected quantity of NO_x emissions for a turboshaft engine.

Figure 29 shows how total NO_x emissions vary for different cruise altitudes of the design mission. Values are shown for NO_x emissions based on both of the baseline engines. The trends are similar to those shown in Figs. 16, 20, and 25 for fuel burn, but the altitudes corresponding to the minima are lower for the tiltrotor and compound helicopter. The compound helicopter has minimum fuel burn and CO_2 at 7,300 m, but minimum NO_x at 5,500 m or 6,400 m, depending on the baseline engine model. Likewise, the tiltrotor has minimum fuel burn and CO_2 at 10,400 m but minimum NO_x at 6,400 m or 8,200 m.

The CO_2 and NO_x emissions (as well as several other minor pollutants) were used to calculate the ATR metric for the three rotorcraft configurations. The variation in the ATR metric with altitude is shown in Figs. 30 and 31. The first plot shows how the metric varies if the low- NO_x baseline engine (CF34) is chosen. The second plot shows the variation for the high- NO_x baseline engine (HTF7000). ATR is most easily expressed in relative terms, where multiple designs are compared against a baseline. In this case, the baseline is the helicopter with a design cruise altitude of

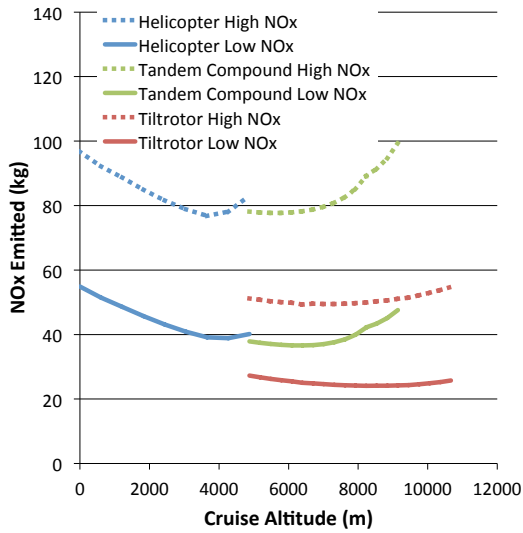


Figure 29. NO_x emissions as a function of altitude

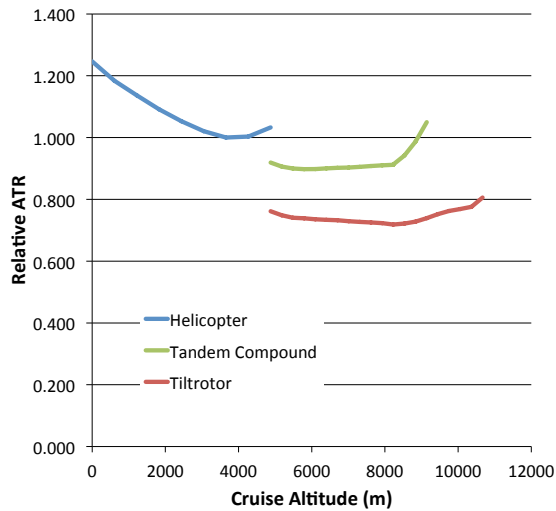


Figure 30. Variation in the ATR metric with cruise altitude with NO_x emissions based on the CF34-3B

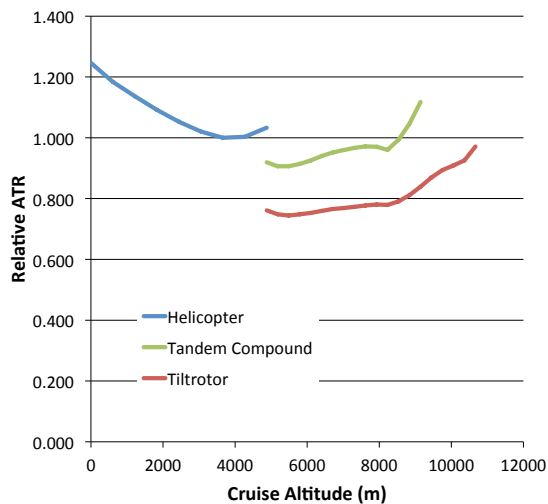


Figure 31. Variation in the ATR metric with cruise altitude with NO_x emissions based on the HTF7000

3,700 m; hence, it has a relative ATR of 1. ATR in this case is calculated assuming one operation per day with a 30-year operating lifetime of the aircraft and a time horizon of 500 years. Temperature impacts after the 30-year operating lifetime are discounted at a rate of three percent per year, so after 50 years, the temperature impacts are discounted by more than 75 percent. This means that shorter-lived emissions, such as NO_x, can have a higher impact than longer-lived emissions, such as CO₂. For a full description of how ATR is calculated, see Refs. 7 and 9.

The results show that of the three rotorcraft configurations, the tiltrotor has the lowest environmental impact, as measured by the ATR metric. When the low-NO_x baseline engine is assumed, ATR for the tiltrotor is minimized at a cruise altitude of 8,200 m. With the high-NO_x baseline engine, ATR is minimized at an altitude of 5,500 m. Recall that fuel burn and CO₂ emissions for the tiltrotor were minimized for a cruise altitude of 10,400 m. A similar effect can be seen in the results for the tandem compound. The reason for the difference is that NO_x emissions lead to the production of ozone, which is a powerful, but short-lived greenhouse gas, whose potency is increased when it is released at higher altitudes. The production of NO_x at high altitudes can therefore lead to more warming, despite decreased CO₂ emissions. The NO_x temperature impact model used for this study only extends down to 4,900 m, and was assumed constant below that altitude. That is why the helicopter results do not show the same discrepancy as the tandem compound and tiltrotor results. The conclusion reached from Figs. 30 and 31 is that if a rotorcraft is designed for minimal environmental impact, it may come at a penalty of increased fuel burn.

Finally, because the minimum-ATR tiltrotor design with the high-NO_x baseline engine flies at such a low altitude, another pass was made at sweeping wing loading and disk loading for this configuration. The results are shown in Figs. 32-34. The trends in the results are very similar to those shown in Figs. 26-28 for a cruise altitude of 10,100 m, except the results at the lower altitude favor a slightly lower wing loading. The best compromise between engine power, fuel burn, and empty weight here appears to be at a wing loading of 390 kg/m² and a disk loading of 59 kg/m²; however, to minimize fuel burn (and therefore CO₂ emissions and the ATR metric), disk loading should be lowered to 49 kg/m². One notable thing about this lower-flying tiltrotor design is that its optimum speed, 437 km/hr, is much lower than that of the higher-flying version, which cruises at 567 km/hr. This result is consistent with those found by Ref. 7, which showed that fixed-wing turbofan aircraft have a reduced environmental impact if they are designed to fly lower and slower.

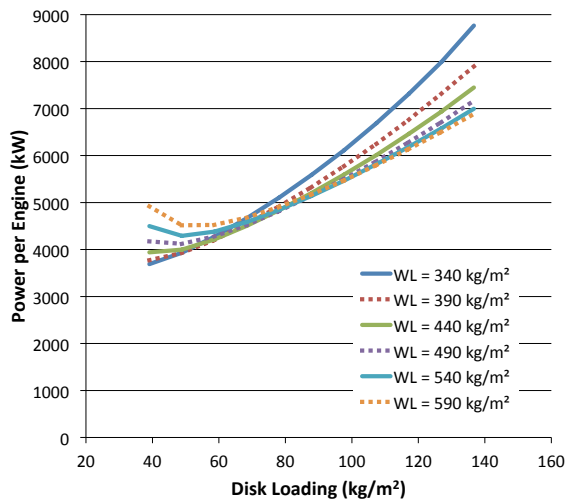


Figure 32. Tiltrotor power per engine as a function of wing loading and disk loading – 5,486 m cruise altitude

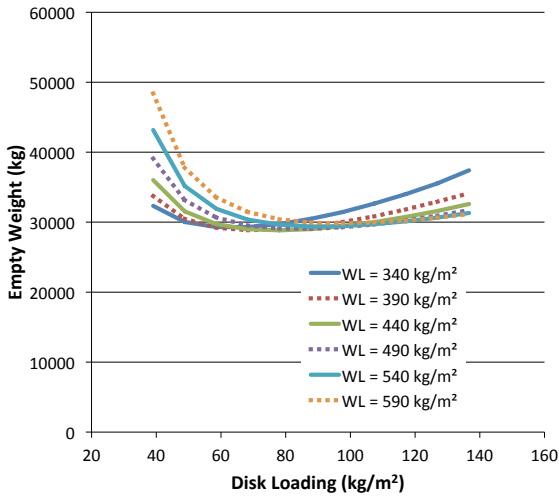


Figure 33. Tiltrotor empty weight as a function of wing loading and disk loading – 5,486 m cruise altitude

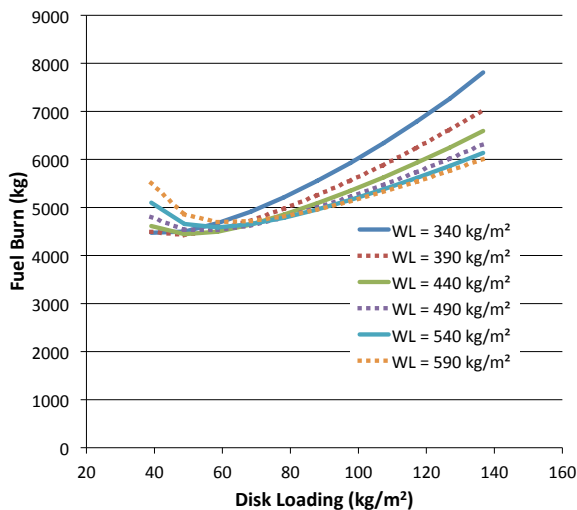


Figure 34. Tiltrotor fuel burn as a function of wing loading and disk loading – 5,486 m cruise altitude

Results Summary

Table 1 contains a comparison of the designs generated by NDARC and CREATION. The first three columns show three different versions of the optimized helicopter. The first is the design generated by NDARC (H90), and the second two show the results from CREATION (HO90) for two different levels of optimization. The optimized helicopters generated by NDARC and CREATION are similar to each other, but the sizing parameters have departed significantly from their baseline values given in Figs. 14 and 15. As shown by column 3 of Table 1, relaxing the OEI requirement on the helicopter has a large impact on the final design, particularly on fuel burn.

The tandem compound (TC90) and tiltrotor (TR90) designs are shown in the fourth and fifth columns, respectively. The rightmost column shows the results for a tiltrotor optimized for minimal environmental impact as measured by the ATR metric (assuming the high- NO_x baseline engine).

Of the three configurations, the tiltrotor has the lowest environmental impact as measured by either the ATR metric or CO_2 emissions. The tiltrotor has a better cruise efficiency (L/D_e of 10.2 vs. 7.6 for the tandem compound and 6.6 for the helicopter), giving it a much lower fuel burn. Using the ATR metric, the environmental impacts of the tandem compound and helicopter are somewhat mitigated by a naturally lower cruise altitude; however, the increased CO_2 and NO_x emissions that accompany the increased fuel burn of these designs offsets any benefit. Because the design mission is heavily cruise dominated, maximizing cruise efficiency is key to minimizing environmental impact. For a design mission that is dominated by hover, the high hover efficiency of the helicopter and tandem compound would certainly cause these configurations to be more competitive.

The final result presented here is that depending on the metric used to measure environmental impact, there is variation in the size, cruise speed, and cruise altitude of the optimal rotorcraft design. Designing for minimum CO_2 emissions alone can lead to a different solution than one that puts a heavy penalty on NO_x emissions.

Table 1. Design comparison

	Helicopters			Compound	Tiltrotors	
	H90	HO90 Step 4	HO90 Step 5	TC90	TR90	TR90 - Min ATR
Mission Fuel (kg)	5,770	5,736	3,718	5,358	4,066	4,427
Empty Weight (kg)	23,330	26,685	26,405	27,772	28,199	30,472
Power per Engine (kW)	3,185	3,133	2,810	4,019	4,362	3,930
Wing Loading (kg/m ²)	–	–	–	440	440	390
Disk Loading (kg/m ²)	39	40	34	54	68	49
Main Rotor Blades	7	7	7	4	4	4
Cruise Altitude (m)	3,700	1,065	2,472	7,300	10,100	5,500
Cruise Speed (km/hr)	306	280	280	419	567	437
CO ₂ Emitted (kg)	18,233	17,816	14,534	16,931	12,849	13,945
NO _x Emitted (kg)*	39 - 77	25	14	38 - 81	25 - 53	25 - 50

* NO_x emissions for the NASA designs were calculated with the modified fuel flow method. ONERA NO_x calculations used the FOCA method.

CONCLUSIONS

There were two goals of this collaborative research effort. The first was to gain an understanding of how targeting reduced environmental impact affects the rotorcraft design process. The second goal was for the collaborators to gain a greater understanding of each other's toolsets and methodologies for rotorcraft design and analysis. With respect to the first goal, the results showed that designing for reduced environmental impact can have a significant impact on the final aircraft design. To be "greener," rotorcraft that typically would fly at high altitudes, such as tiltrotors, should fly lower and slower to reduce the impact of NO_x emissions. This can come at a cost of higher fuel burn and CO₂ emissions.

With respect to the second goal, the software toolsets were able to produce similar results for both a helicopter and a tiltrotor configuration. Results for rotor power and engine fuel consumption were very similar between the NASA and ONERA tools. Also, the rotorcraft design software tools NDARC and CREATION were able to produce very similar baseline helicopter designs. The optimized helicopter designs from both tools diverged from one another, but were still similar. In the future, the capabilities of NDARC and CREATION will likely be more closely matched, allowing for easier collaboration between the two sides.

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