Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

A Multidisciplinary Simulation Framework for Optimization of Rotorcraft Operations and Environmental Impact

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Problem area
Rotorcraft mission performance analysis has always been an important topic for the rotorcraft industry. This topic is now raising even more interest as aspects related to gas emissions and noise gain more importance for environmental and social impact assessments. The present work illustrates a multidisciplinary analysis case where a selected helicopter maneuver is optimized in order to minimize the noise and exhaust gas emissions footprints under specific operational or environmental constraints. For this purpose, an integrated tool is being developed within the JTI Clean Sky Green Rotorcraft initiative that is capable of computing and optimizing flight paths against noise and gas emissions as well as assessing its environmental impact. This simulation framework tool is the result of a collaborative effort between LMS International (BE), National Aerospace Laboratory NLR (NL) and Cranfield University (UK).

Description of work
In order to simulate the characteristics of a specific trajectory, as well as to evaluate the gas emissions and noise that are produced during the rotorcraft's operation, three computational

This report is based on a presentation held at the 2nd International Conference on Engineering Optimization, Lisbon, September 6-9, 2010.

models have been integrated into the simulation tool. These models consist of a rotorcraft flight mechanics tool (jointly developed in a European project), a rotorcraft environmental noise analysis tool (jointly developed in a European project), and an engine performance and emissions tool developed at NLR. The integrated process has been created in order for the three simulation tools to communicate with each other, and iteration loops have been added to account for fuel burn during the course of the mission. The multidisciplinary integrated process has been performed with the deployment of the OPTIMUS process and simulation integration framework developed by NOESIS Solutions, subsidiary of LMS International.

Results and conclusions

The optimization processes carried out are based on OPTIMUS' built-in optimization algorithms as well as on algorithms developed at NLR. A comparative evaluation between baseline and optimized trajectory's results has been waged for the purpose of quantifying the operational profit (in terms of fuel required) gained by the helicopter's operation within the path of an optimized trajectory under specific constraints.

Applicability

The application of the methodology to a case study and the actual gain in terms of environmental impact, demonstrates the validity of this integration and optimization process for a class of rotorcraft missions.

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A Multidisciplinary Simulation Framework for Optimization of Rotorcraft Operations and Environmental Impact

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Summary

Rotorcraft mission performance analysis has always been an important topic for the rotorcraft industry. This topic is now raising even more interest as aspects related to gas emissions and noise gain more importance for environmental and social impact assessments. The present work illustrates a multidisciplinary analysis case where a selected helicopter maneuver is optimized in order to minimize the noise and exhaust gas emissions footprints under specific operational or environmental constraints. For this purpose, an integrated tool is being developed within the JTI Clean Sky Green Rotorcraft initiative that is capable of computing and optimizing flight paths against noise and gas emissions as well as assessing its environmental impact. This simulation framework tool is the result of a collaborative effort between LMS International (BE), National Aerospace Laboratory NLR (NL) and Cranfield University (UK).

In order to simulate the characteristics of a specific trajectory, as well as to evaluate the gas emissions and noise that are produced during the rotorcraft's operation, three computational models have been integrated into the simulation tool. These models consist of a rotorcraft flight mechanics tool (jointly developed in a European project), a rotorcraft environmental noise analysis tool (jointly developed in a European project), and an engine performance and emissions tool developed at NLR. The integrated process has been created in order for the three simulation tools to communicate with each other, and iteration loops have been added to account for fuel burn during the course of the mission. The multidisciplinary integrated process has been performed with the deployment of the OPTIMUS process and simulation integration framework developed by NOESIS Solutions, subsidiary of LMS International. The optimization processes carried out for the purpose of this work are based on OPTIMUS' built-in optimization algorithms as well as on algorithms developed at NLR. A comparative evaluation between a baseline and the optimized trajectory's results has been waged for the purpose of quantifying the operational profit (in terms of fuel required) gained by the helicopter's operation within the path of an optimized trajectory under specific constraints.

The application of the aforementioned methodology to a case study and the actual gain in terms of environmental impact, demonstrates the validity of this integration and optimization process for a class of rotorcraft missions, based on the simulation performed.

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Contents

Abbreviations

ACARE	Advisory Council for Aeronautics Research in Europe
BE	Belgium
Cat-A	Category A
CFD	Computational Fluid Dynamics
CO	Carbon Oxide
dB	deciBel
DOE	Design of Experiment
EPNdB	Effective Perceived Noise, deciBel
EPNL	Effective Perceived Noise Level
EUROPA	European Rotorcraft Performance Analysis
GSP	Gas-turbine Simulation program
HELENA	Helicopter Environmental Noise Analysis
ITD	Integrated Technology Demonstrator
JTI	Joint Technology Initiative
LAE	Abbreviation of Sound Exposure Level
LHD	Latin Hypercube Design
LMS	Leuven Measurements Systems
MBB	Messerschmitt-Bölkow-Blohm
NL	Netherlands
NLPQL	Software code to solve constrained Non Linear Programming problems
NLR	National Aerospace Laboratory NLR
NOx	Nitrogen Oxide
PhoeniX	Platform Hosting Operational and Environmental Investigations for Rotorcraft
PNdB	Perceived Noise, decibel
PNL	Perceived Noise Level
PNLT	Tone-corrected Perceived Noise Level
PNLTM	Maximum tone-corrected Perceived Noise Level
RSM	Response Surface Model
SFC	Specific Fuel Consumption
TDP	Take-off Decision Point
UK	United Kingdom

1 Introduction

The usage of helicopters has been until now concentrated in activities such as offshore transport, medical evacuation, rescue, civil protection, aerial work and law enforcement. These activities amount to about 1.500.000 flight hours per year to be compared with around 10.000.000 hours flown by the European commercial airlines. This volume of helicopter activity represents the pure minimum required to satisfy today's primary needs of the population and, as such, it is commonly accepted.
Such rotorcraft operations are expected to grow sharply in the future to face the European citizen's demand for a safer and more secure society. Considering only the case of medical services as an example, the number of flights will drastically increase as a result from the current development of advanced curing techniques and from the specialization of hospitals. The helicopter is definitely the most efficient vehicle to achieve safe and quick transport of patients between hospitals and to deliver living organs for transplantation.
In addition, the rotorcraft traffic for passenger transport that is presently only a marginal activity is expected to develop rapidly as it is driven by the large growth in passenger air travel demand that is foreseen for the 2015 – 2020 period (2 to 3 fold increases). Helicopter shuttle operations carrying passengers from city heliports to airports, or even flights between cities without airports and for which efficient surface transport could not be effectively developed (e.g. in mountainous areas, or for connection of islands to mainland where ground infrastructure is limited).
As a consequence of this expected growth of traffic, the rotorcraft contribution to the environmental impact of air transport which appears today as negligible would become more significant in the next decade. The Rotorcraft ITD in Clean Sky [Ref. 1] responds to the challenge of minimizing the impact of sharply increasing rotorcraft traffic (including the introduction of tilt-rotors) through a much more efficient usage of energy and through a drastic reduction of greenhouse gas emission and noise footprints throughout the whole mission spectrum.
The present rotorcraft activities imply burning the equivalent of 400000 tons of fuel per year in the European Community. With the present technologies, this figure is expected at least to quadruplicate as a result of the traffic augmentation in the next 20 years. The final objective of all Research & Development performed at national and European levels is to come back within 20 years to the present global level of impact on the environment while sustaining the same expected growth of helicopter services.
The partial objective to be achieved within the next 10 years as resulting from Clean Sky outputs of the Green Rotorcraft ITD and contributions from other ITDs, along with outputs of other already launched technology programs, consists in halving the specific impact of any

rotorcraft operation on the environment. In detail, taking into account the year 2000 like baseline and consistent with ACARE targets, the objectives are reported in the diagram below.

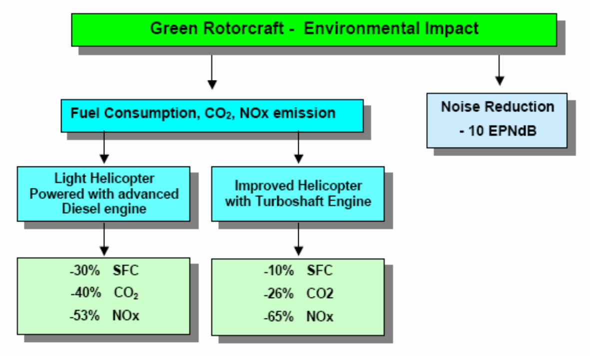


Figure 1: Green Rotorcraft objectives

The present work illustrates a multidisciplinary analysis case where a selected helicopter maneuver is optimized in order to minimize the noise and emissions footprints under specific operational or environmental constraints. For this purpose, an integrated tool is being developed within the JTI Green Rotorcraft initiative that is capable of computing and optimizing flight paths against noise and gas emissions as well as assessing its environmental impact. This simulation framework tool is the result of a collaborative effort between LMS International (BE), National Aerospace Laboratory NLR (NL) and Cranfield University (UK).

2 Application case: rotorcraft mission optimization

In order to assess and optimize the environmental impact of helicopter missions, a representative helicopter model and a typical maneuver have been selected. The helicopter model that has been implemented is the MBB Bo 105. This is a light helicopter with a two Allison 250-C20B turbine engines originally developed by Bölkow, which became a part of Eurocopter in 1991.

Figure 2: The MBB Bo 105 helicopter used for the analysis case (courtesy of Eurocopter)

The type of maneuver selected for the purpose of this work is a typical Category A (CAT-A) take-off maneuver. Generally CAT-A means that the helicopter is flown in such a way, that in case of a single engine failure during take off or landing, the helicopter can either safely continue the flight or safely abort it. Basically it is an operating procedure like in fixed wing airline transport.

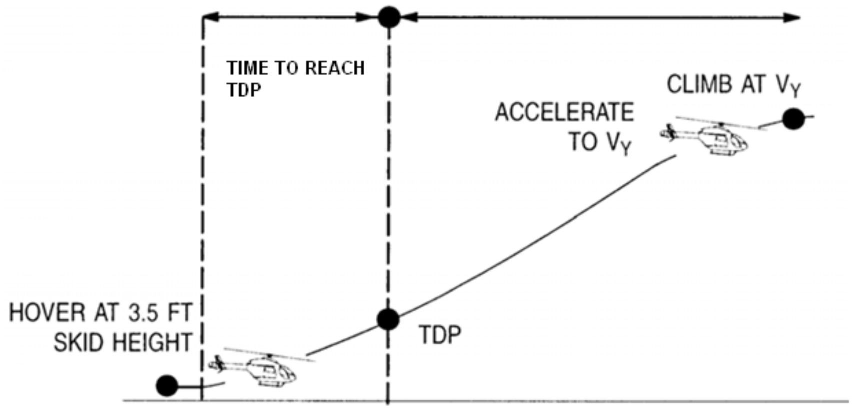


Figure 3: Category A take off maneuver

The CAT-A take-off maneuver as used in the analysis consists of the following steps:

- The helicopter starts the take-off from a hover position, then accelerates to a predefined airspeed and upon reaching that speed starts climbing to the TDP (take-off decision point). This is the point in a take-off profile from which a safe and continued take off capability after an engine failure is assured.
- After TDP, the helicopter adjusts the air speed to the speed to hold during the climb.
- Finally at a given height the helicopter does an initial turn.

This maneuver will be simulated a number of times by changing the typical parameters that influence it, in order to find the best combination of these parameters that minimize the noise on the ground and the emissions for the resulting trajectory. The gain in terms of gas emissions and noise reduction will be computed and a comparison between the baseline maneuver and the optimal maneuver found by using the multidisciplinary tool will be presented. With the present case, also the validity of the tool will be demonstrated as well as its applicability to other types of maneuvers and helicopter models.
For the present case, the input parameters that determine the trajectory profile and that can change during the optimization process are:

Table 1: Trajectory optimization parameters

Input Parameter	Nominal Value	Min	Max
TDP height (ft)	35	20	50
Air speed to start climbing (kts)	30	30	40
Target air sp eed (Vy) to hold during cli mb (kts)	65 60		80
Engine torque to set during climb (%)	65	60	70
Target height to start initial turn (ft)	100	100	500

Their meaning is the following:

- *TDP height (ft)*: is the height of the take-off decision point. The nominal value for the Bo 105 helicopter during a CAT A take-off trajectory is 35ft, but in order to find the optimum point this value can change during the simulation between 20 and 50ft.
- *Air speed to start climbing (kts)*: is the initial speed that the helicopter keeps before reaching the TDP point. The nominal value is 30kts (1kt is equal to one nautical mile per hour); in order to get the optimum point this value can change between 30kts and 40kts.
- *Target air speed (Vy) to hold during climb (kts)*: is the air speed to hold during the climb after the TDP point, the nominal value is 65kts and this value can change between 60 and 80kts.
- *Engine torque to set during climb (%)*: is the percentage use of engine's torque during the climb, the nominal percentage is 65% but this percentage, for the optimization can change between 60 and 70%.
- *Target height to start initial turn*: is the height where the helicopter starts the initial turn, the nominal value is 100ft but in order to get the nominal point in terms of minimizing the emissions and the noise perceived, this value can change between 100 and 500ft.

3 Multidisciplinary Simulation Framework PhoeniX

In order to assess the environmental impact generated by a specific trajectory, an integrated multidisciplinary simulation framework has been created for this purpose. This framework has been named PhoeniX (Platform Hosting Operational and ENvironmental Investigations for Rotorcraft) and consists of three computational tools developed jointly by LMS International (BE), National Aerospace Laboratory NLR (NL) and Cranfield University (UK) federated with a fourth process integration tool [Refs. 6, 7]. The first three tools are:

- EUROPA: A rotorcraft flight mechanics tool
- HELENA: A rotorcraft environmental noise analysis model
- GSP: An engine performance and gas emission tool

The multidisciplinary federation of these three tools has been performed with LMS OPTIMUS. This last tool has also been used for the optimization process. An architectural overview of the PhoeniX framework is given in Figure 4.

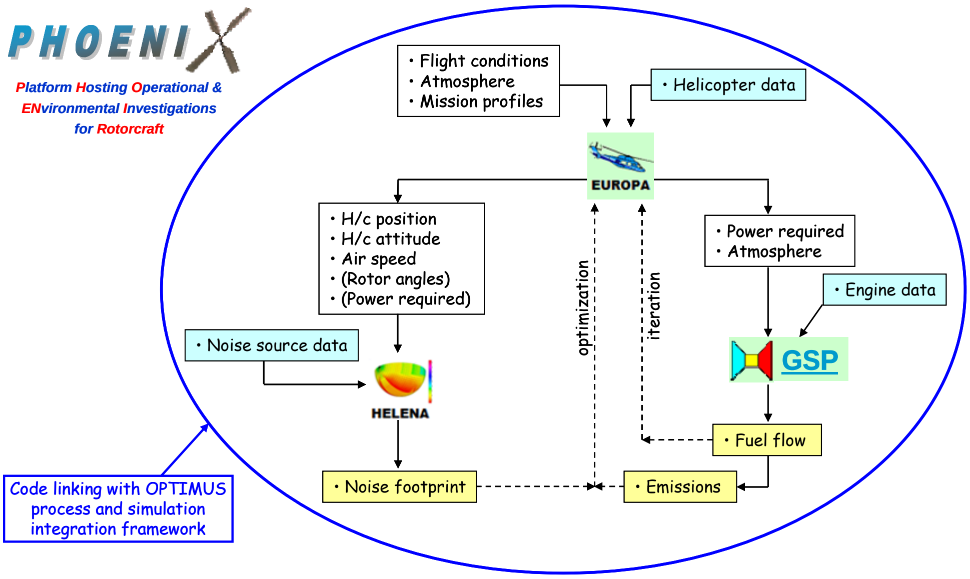


Figure 4: PhoeniX Framework Architectural overview

European Rotorcraft Performance Analysis code (EUROPA)

EUROPA (EUropean ROtorcraft Performance Analysis) is a helicopter flight mechanics code, designed to calculate helicopter steady state (trim) and dynamic (maneuver) performance. It is ideally suited to determine (optimized) take-off and landing flight paths. The code has been developed and input models have been validated in the European RESPECT project. A version dedicated to tilt rotor aircraft has been developed in the European NICETRIP project. The flight mechanics simulation generates a helicopter's trajectory in order to analyze the performance and the environmental impact, in terms of gas emissions and noise, of existing helicopter configurations in a range of flight conditions. Its scope is to contribute to the development of new designs and to asses the feasibility of various design alternatives for the purpose of minimizing the noise and the environmental impact. EUROPA uses a generic helicopter mission description where properties such as flight conditions, atmospheric conditions and helicopter data are defined by the user. The helicopter flight path output is truncated in a number of flight segments, with each segment containing information such as position attitude, tip path plane angles etc. as a function of time. EUROPA will provide this information to the other tools for noise and gas emissions estimations along each segment of the trajectory.

Helicopter Environmental Noise Analysis (HELENA)

In order to assess the noise footprint of the flown trajectory computed by EUROPA, the HELENA (HELicopter Environmental Noise Analysis) tool has been used. The HELENA tool has been developed within the European Friendcopter research project and is capable of computing and generating noise footprints on the ground starting from experimental or numerical (CFD) noise data. The noise propagation models used in HELENA have been specifically tailored for rotorcraft noise (that is very different from aircraft generated noise) and take into account also distance (short and long), wind effects, atmospheric absorption effects and ground reflection and shielding effects. Helicopter noise models used by HELENA have been validated with dedicated flight tests. As a result of the analysis of the trajectory data received by EUROPA, HELENA computes the noise level at the ground for each trajectory segment. In particular, HELENA computes the noise with three different metrics:

- PNLTM: Maximum tone-corrected Perceived Noise Level
- EPNL: Effective Perceived Noise Level
- LAE: abbreviation of Sound Exposure Level

These metrics are scales developed to measure the perceived noisiness of jet aircraft and rotorcraft by observers on the ground. The PNL, Perceived Noise Level, metric converts the decibel scale into a series of increments; then this scale, called *noy* scale, can be converted into PNdB. The equation expressing this relationship is:

$$PNdB = 40 + 10\log_2(noy) \tag{1}$$

The EPNL is a modification of the PNL to take into account tone components in aircraft/rotorcraft broad band noise, as well the duration of the noise. It is measured in EPNdB, and defined as the Perceived Noise Level in PNdB plus a tone correction and a duration correction. The EPNL measurement is based on the following equation:

$$EPNL = 10\log_{10}\left[\frac{1}{T}\int_{t_1}^{t_2} 10^{\frac{PNLT}{10}}\,dt\right] \quad (dB) \tag{2}$$

Where PNLT is the 'Tone-corrected Perceived Noise Level' and t1 and t2 are the so-called '10dB down' points. The *PNLT* scale is equal to the PNL scale plus a correction value for taking into account the presence of discrete frequency components.

The LAE metric is the symbol abbreviation for Sound Exposure Level. It is the most common measure of cumulative noise exposure for a single rotorcraft flyover. Mathematically, is defined as the level, in decibels, of the time integral of squared 'A'-weighted sound pressure (Pa) over a given time period or event, with reference to the square of the standard reference sound pressure (P0) of 20 micropascals and a reference duration of one second.

This unit is defined by the expression:

$$L_{AE} = 10\log_{10}\left[\frac{1}{T_0}\int_{t_1}^{t_2}\left(\frac{P_A(t)}{P_0}\right)^2 dt\right] \quad (dB) \tag{3}$$

Where T_0 is the reference integration time of one second and (t_2-t_1) is the integration time interval.

Gas Turbine Simulation Program (GSP)

The third tool integrated in the PhoeniX platform is the Gas turbine Simulation Program (GSP). GSP is a in-house tool developed at NLR to simulate gas turbine thermodynamic cycles for engine performance (fuel flow, power) and exhaust gas emissions. GSP implements a one dimensional engine flow model and can model any type of gas turbine engine configuration. It can handle both steady state and transient calculations taking into account inlet conditions, losses and deterioration.

It has not been possible (yet) to fully validate the helicopter mathematical engine models used within GSP, as measured exhaust gas emission data for helicopter engines are not available. It is anticipated to perform such emission measurements within the Clean Sky project.

For the present work GSP has been used to compute the power available and the fuel flow for mission mass calculation in a coupled simulation with the EUROPA code. In this case, GSP retrieves the power required and the atmospheric data from EUROPA and uses also the engine data from the database. With these data at each instant in time, GSP determines the fuel consumption for mission mass calculation and generates exhaust gas emissions.

OPTIMUS Simulation Framework Toolkit

The federation of the aforementioned simulation tools has been carried out with LMS OPTIMUS [Ref. 5]. OPTIMUS is a simulation framework toolkit and a flexible design environment which can be used to create multidisciplinary simulation frameworks and to evaluate multiple design alternatives. OPTIMUS can be used to translate the logical elements and relations of a multidisciplinary simulation process into an actionable computational framework that can automatically execute a number of calculation steps without user intervention iteratively.

Having its own integrated variety of optimization sequences ranging from single-objective local optimization to multi-objective global optimization methods, OPTIMUS can be used also for trade-off and optimization studies. The OPTIMUS implementation of the PhoeniX architectural diagram of Figure 4 is shown in Figure 5.

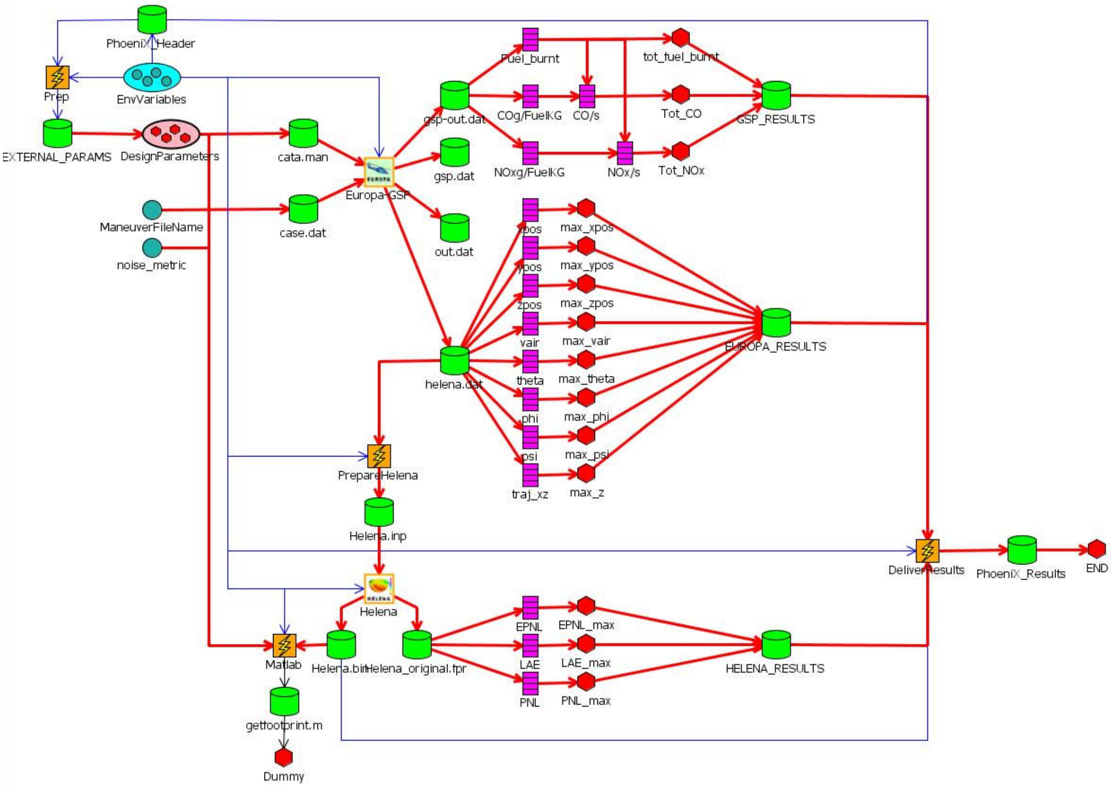


Figure 5: Implementation of the PhoeniX platform using OPTIMUS

The OPTIMUS implementation of the PhoeniX framework allows the execution of the multidisciplinary workflow for each helicopter mission profile defined. For the present case, the mission profile selected is the CAT-A maneuver already introduced. Each mission is defined by a set of flight and helicopter conditions that can be changed at every experiment and are identified by a set of values of the input parameters

For the present case, the single assessment of the noise and gas emissions for a selected set of values for the input parameters includes the following operations:

- EUROPA accepts the helicopter data, the flight and the atmosphere conditions as input. Based on these user defined conditions, EUROPA will calculate a flight path divided in different segments. For each segment, EUROPA will return the helicopter's position, the time to reach the position, the attitude and tip path plane angles, the power required and the atmospheric conditions.
- GSP is coupled inside EUROPA: for each time segment calculated by EUROPA, GSP retrieves the information about the atmospheric condition (pressure and temperature) and the power required. It uses this information to calculate the fuel burnt and the emissions' quantity of CO, NOx and Smoke Number produced during every segment. OPTIMUS then extracts these results and post processes them to know the total quantities of fuel burnt and polluting gases produced during the entire trajectory.

- After the successful convergence of the mission fuel by EUROPA and GSP, OPTIMUS automatically reads EUROPA's trajectory output file and passes this data to HELENA with the appropriate format in order to perform the noise assessment. HELENA determines the noise footprints for the given flight conditions. After than HELENA calculates the level of the three metric of noise for each segment, OPTIMUS extracts the results and collects the data needed for the further analysis.

Output quantities definition

As a consequence, a set of output parameters has been selected as representative of the environmental (noise and gas emission) performance of the maneuver. In particular:

Table 2: Output variables

Output variables	**Measurement Units**
Maximum LAE	dB
Total Fuel Burnt	Kilograms
Total CO Emitted	Grams
Total NOx Emitted	Grams

4 Analysis Case Implementation and Results

The purpose of this work is the CAT-A take off trajectory's optimization of a helicopter, in order to find the best trajectory that minimizes noise footprint and gas emissions. To achieve this goal, a design analysis and optimization methodology has been developed to carefully investigate the helicopter behavior and be able to assess the influence of the input parameters on the final performances. The optimization methodology has been specifically developed to achieve the smallest computational effort possible, thus reducing to the minimum the number of needed computations.

Optimization strategy

The optimization strategy developed for the present analysis consists of two logical steps: the design exploration and approximation and the optimization approach. The first step is divided in two parts: the construction of the Design of Experiments (DOE) [Ref. 2] and the synthesis of a meta-model based on the DOE results. A DOE is a systematic approach to get the maximum amount of information out of various types of experiments while minimizing the number of experiments. There are different kinds of DOE, in this work the Latin Hypercube Designs (LHDs) DOE has been used. After the DOE, the construction of a Response Surface Model (RSM) [Ref. 3] has been carried out based on the experiments of the DOE. The RSM is a

collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables. Using DOE methods combined with response surface modeling, one can efficiently predict the response of the system at all the points of the design space with a small error. The RSM methodology allows for further processing of the DOE results. Examples are the analysis of design variables contributions, 2D and 3D plotting, and foremost utilization of the RSM for optimization. Consequently, not only the lengthy and costly simulation runs can be reduced, but also the inherent trend (often non-linear) can be correctly predicted. When utilizing RSMs for optimization one has to always be cautious and ensure sufficient quality of the RSM.
The overall optimization strategy adopted can be summarized in the following steps:

- Step 1
  - Perform a design of experiments to explore the design space in specific locations
  - Build a response surface model based on the DoE results in order to approximate the response of the system
- Step 2:
  - Perform a single objective global optimization procedure using the response model for each of the output quantities
  - Once the global optimum configurations have been identified, perform a single objective local optimization using the response surface method for each of the output quantities
- Step 3 (optional)
  - Perform a single objective, multiple target minimization in order to minimize both noise and gas emissions

Design of Experiments analysis and results

The first step of the optimization strategy, is the exploration of the design space with a Design of Experiments procedure. Design of Experiments (DOE) is an automatic and systematic approach to get the maximum amount of information out of various types of experiments while minimizing the number of experiments. The DoE is a detailed experimental plan, studying the influence of design factors on the design responses. There are different types of DOE depending on the different ways to build an experimental plan; however the primary goal is always to extract the maximum amount of information concerning the influence of design factors on the system performance. Since executing the experiments can be a time-consuming task, further exploration can be done trough Response Surface Models, a mathematical approximation methodology that may predict values based on the experiments calculated by the DOE.
For the present case, a Latin Hypercube DoE (LHD) has been selected for design space exploration (for a complete description of LHDs refer to Ref's 2, 4, 5). A Latin-Hypercube DOE method belongs to the category of random methods so that design points are chosen based on a random process. However, in Latin Hypercube the design points are not completely random, as complete randomness can lead to a design filled with clustered points, which is not an

interesting situation for exploration purposes. Instead, in LHD points are as much space-filling as possible. In statistical sampling, structured randomization is achieved through a Latin square, which is defined as a grid containing sample positions, if and only if there is only one sample in each row and each column. A Latin-hypercube DOE will generalize this idea in multiple dimensions by forcing only one sample on each axis-aligned hyper plane.

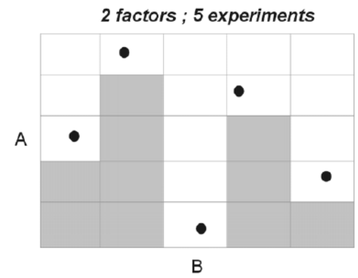
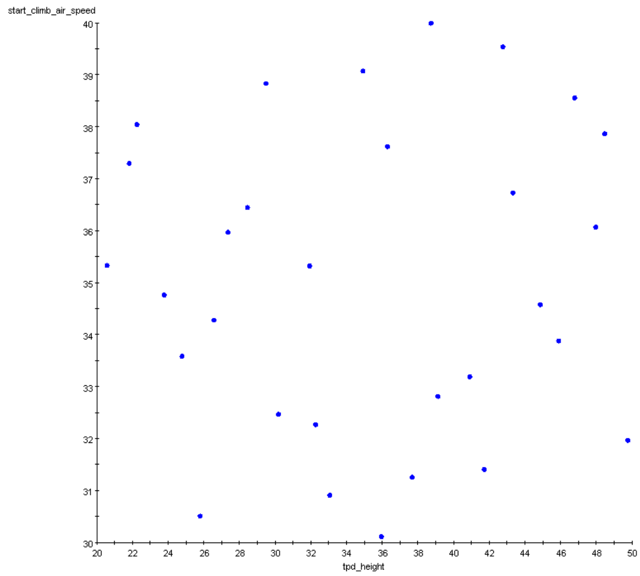


Figure 6: Example of a simple LHD

The advantage of the LHD random method is that the experiments executed cover the entire domain of interest with sufficient uniformity and are not grouped in a portion of it. This LHD DOE method is extremely effective if one wants to analyze the domain with a fixed number of experiments. Of course, the number of experiments depends on the dimensionality of the case under study. For the present case, a LHD of 30 experiments has been performed (Figure 7a). The DoE results can be used to estimate the principal linear correlation between input variables and outputs and between outputs and themselves. The principal linear correlation coefficient indicates the amount and type of average dependency of a variable w.r.t. another one.



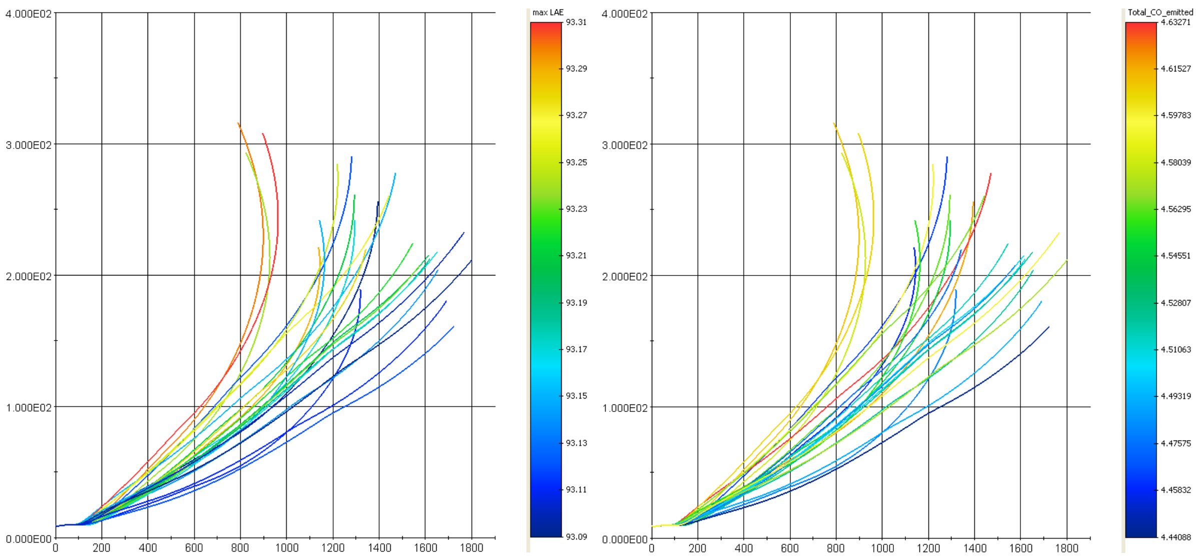
(a)

	tpd_height	start_climb_air_s	target_ini_air_sp	torque_climb	height_start_tu	max LAE	Total_Fuel_Burn	Total_CO_emittec	Total_NOX_emitte
tpd_height	1.000	0.034	-0.013	-0.028	0.049	0.016	-0.029	-0.030	-0.029
start_climb_air_speed	0.034	1.000	-0.022	-0.041	-0.054	0.013	-0.135	-0.169	-0.123
target_ini_air_speed	-0.013	-0.022	1.000	-0.046	-0.001	-0.997	-0.035	-0.094	-0.034
torque_climb	-0.028	-0.041	-0.046	1.000	-0.105	0.055	0.995	0.990	0.996
height_start_turn	0.049	-0.054	-0.001	-0.105	1.000	-0.025	-0.095	-0.099	-0.095
max LAE	0.016	0.013	-0.997	0.055	-0.025	1.000	0.045	0.104	0.044
Total_Fuel_Burnt	-0.029	-0.135	-0.035	0.995	-0.095	0.045	1.000	0.997	1.000
Total_CO_emitted	-0.030	-0.169	-0.094	0.990	-0.099	0.104	0.997	1.000	0.995
Total_NOX_emitted	-0.029	-0.123	-0.034	0.996	-0.095	0.044	1.000	0.995	1.000

(b)

Figure 7: Latin Hypercube DoE scatter plot (a) and linear correlation estimation between inputs and outputs (b)

The correlation can be direct or indirect and can range from -1 to 1. A direct correlation has a positive non zero value and indicates that if a variable increases, also the correlated one may increase (not necessarily of a proportional amount). An indirect correlation has a negative non zero value and indicates that there is an indirect relation between the two correlated variables. From the analysis of the correlation matrix obtained with the LHD DoE (Figure 7b), one can observe that there is a strong indirect correlation between the *max LAE* and the "*Target air speed (Vy) to hold during climb*", while there is a strong direct correlation between the amount of gas (CO and NOx) and fuel emissions and the "*Engine torque to set during climb*". All the other input variables have a very small correlation value with respect to the previous two ones and thus can be considered as having a negligible effect on the output performance. Finally, it can be observed that there is a very low correlation between the amount of fuel and gas emissions and the noise produced. Thus it appears to be possible to find an optimal CAT-A trajectory that can both minimize the fuel and gas emissions and the noise at the same time. This indicates that the additional 3rd step can be performed. In view of the optimization process, improving one noise or gas characteristic, will also improve the other correlated noise or gas characteristics. This can be explained by observing the correlation matrix and noting the strong direct correlation, for example, among the three gas and fuel emission indicators. As a consequence, the optimization process to reduce the noise and the emission characteristics can focus only on the *max LAE* output as representative of the noise emissions and the *Total CO emitted* output as representative of the fuel and gas emissions.
In Figure 8 a colorization of the computed trajectories has been made to discriminate, among the trajectories computed by the LHD procedure, the ones that exhibit more noise or more fuel & gas emissions.

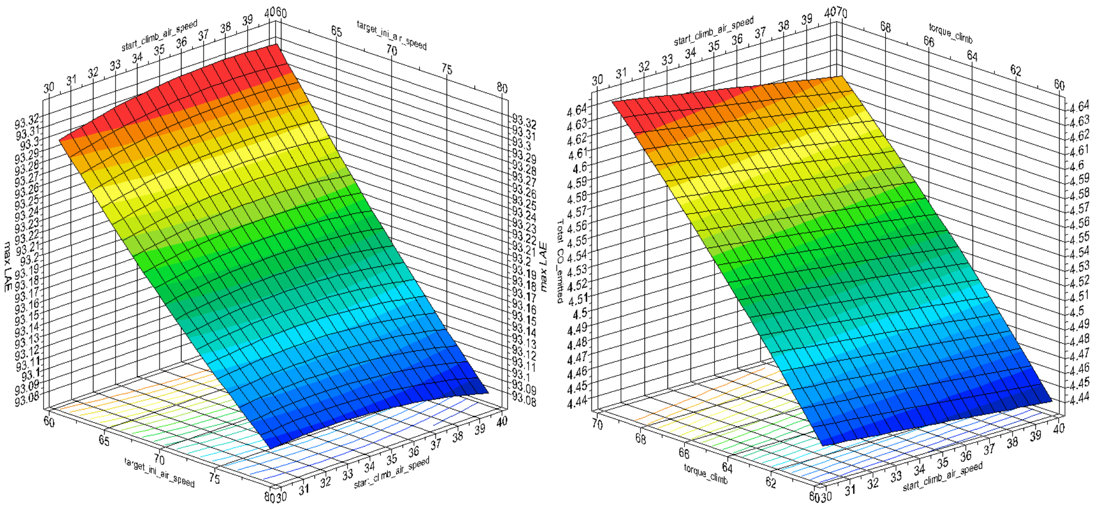


(a) (b)

Figure 8: Colored trajectory visualization: with max LAE index (a) or with Total CO emitted (b)

Response surface model

Following the execution of the LHD DOE, a response surface model has been created to approximate the response of the system for the two quantities of interest: *max LAE* and *Total CO emitted*.



(a) (b)

Figure 9: Cross sections of the response models for the max LAE index (a) and Total CO emitted (b)

For the present case, two least squares fitting Taylor polynomials have been used to approximate the two responses of interest. A quality check for their approximating and predictive quality indexes has been performed in order to ensure that the RSM models have sufficient approximation and prediction accuracy to be used for optimization purposes. As mentioned earlier, the final optimal configuration should be eventually compared with simulation in order to assess the absolute error between the meta-model and the simulation. Given the mathematical formulation of the response models, using them in optimization processes considerably reduces the computational time. Even for short running simulations, the fraction of seconds required to evaluate a response model allows the optimization time to be drastically reduced.

Optimization results

In order to perform the second step of the optimization strategy, two single objective optimization processes have been deployed: one to minimize only the max LAE index and the other to minimize only the total CO emitted.

Both optimization processes start from a baseline configuration defined as the nominal configuration mentioned in Table 1. The two optimization processes are, in their turn, divided each in two sub steps: a global and a local optimization procedures. For each of the quantities of interest, the combined use of a global and a local optimization process allows the identification of the global optimal configuration with high accuracy. In the present case, the global optimization methodology used has been the Differential Evolution algorithm and the local optimization strategy has been based on the NLPQL algorithm. The results of both optimization procedures are reported in Table 3 and Table 4, respectively, for the max LAE and the Total CO Emitted. In these tables, the baseline configuration is compared with the results of the global optimization procedure using the differential evolution algorithm and the subsequent local optimization procedure using the NLPQL algorithm.

Table 3: Results of the global and local optimization procedure to minimize the max LAE index

Baseline	configuration	Differential Evolution Optimum	NLPQL Optimum	Benefit (%)
Inputs				
tpd_height (ft)	35	20.2885	20.2885	
start_climb_air_speed (kts)	30	39.9425	39.9425	
target_ini_air_speed (kts)	65	79.9752	80.0552	
torque_climb (%)	65	69.9988	69.9988	
height_start_turn (ft)	100	498.7528	498.7528	
Outputs				
max LAE (dB)	**93.2421 93.0**	**416**	**93.0407**	-0.2%
Total_Fuel_Burnt (Kg)	3.2796	3.4820	3.4820	+6.2%
Total_CO_emitted (g)	4.5630 4.6170		4.6169	+1.2%
Total_NOx_emitted (g)	12.0492 13.3804		13.3804	+11.0%
GOAL 93.2421		93.0416	93.0407	+0.2%

Table 4: Results of the global and local optimization procedure to minimize the Total CO emitted index

Baseline	configuration	Differential Evolution Optimum	NLPQL Optimum	Benefit (%)
Inputs				
tpd_height (ft)	35	20.0075	20.0075	
start_climb_air_speed (kts)	30	39.9956	39.9956	
target_ini_air_speed (kts)	65	79.9922	79.9922	
torque_climb (%)	65	60.0001	59.9401	
height_start_turn (ft)	100	149.9816	149.9816	
Outputs				
max LAE (dB)	93.2421	93.0638	93.0632	-0.2%
Total_Fuel_Burnt (Kg)	3.2796	2.9923	2.9894	-8.8%
Total_CO_emitted (g)	**4.5630 4.43**	**10**	**4.4297**	-2.9%
Total_NOx_emitted (g)	12.0492 10.3394		10.3228	-14.3%
GOAL 4.5630		4.4310	4.4297	-2.9%

Observing the results obtained, the two optimal configurations found are clearly improving only one of the objectives at a time. However, given the observation previously made on the low correlation between the two objectives, a third optimization procedure can be performed, trying to minimize both objectives (noise and emissions) at the same time. The results of this third optimization, always based on the response models previously computed, are reported in Table 5.

The newly found optimal configuration shows improvements on both the noise and the fuel & gas emissions. This configuration, obtained with the use of the response models, has been compared with direct simulation. The results of the comparison are reported in Table 6.

Table 5: Results of the global optimization procedure to minimize both the max LAE and the Total CO emitted indexes

Baseline	configuration	Differential Evolution Optimum	Benefit (%)
Inputs			
tpd_height (ft)	35	20.0844	
start_climb_air_speed (kts)	30	39.9912	
target_ini_air_speed (kts)	65	79.9978	
torque_climb (%)	65	60.0854	
height_start_turn (ft)	100	496.4654	
Outputs			
max LAE (dB)	**93.2421 93.0**	**577**	-0.2%
Total_Fuel_Burnt (Kg)	3.2796	2.9996	-8.5%
Total_CO_emitted (g)	**4.5630 4.43**	**65**	-2.8%
Total_NOx_emitted (g)	12.0492 10.3843		-13.8%
GOAL 8.71E+09		8.68E+09	-0.3%

Table 6: Comparison of the two optimal configurations, one with RSM and the other with direct simulation

Output variables	**Units**	**Optimal RSM**	**Optimal Simulation**
Maximum LAE	dB	93.0577	93.08
Total Fuel Burnt	Kilograms	2.9996	2.9989
Total CO Emitted	Grams	4.4365	4.4351
Total NOx Emitted	Grams	10.3843	10.3799

5 Conclusions

This work enabled to develop an effective and efficient methodology for the optimization of a helicopter trajectory, in agreement with the ACARE objectives and of Clean Sky JTI. It has demonstrated that an improvement is possible to reduce the environmental impact of a helicopter in terms of noise perceived on the ground and in terms of fuel burnt and emissions of CO and NOx.

The helicopter model that has been implemented for the analysis is the MBB Bo 105, a light helicopter with two Allison 250-C20B turbine engines and the maneuver type selected for the purpose of this work is a typical CAT A take-off trajectory for a helicopter of similar specification. A simulation workflow has been built using the OPTIMUS tool and the GRC PhoeniX platform in order to predict the noise and the gas emissions for the selected maneuver. The hybrid optimization strategy implemented has allowed an efficient and accurate optimization of the helicopter maneuver, highlighting the dependencies between input and output variables and identifying the final optimal configuration that minimized both noise and fuel & gas emissions. More work is required to validate the complete methodology and further extend it with other functionalities.

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References

1. Clean Sky JTI (Joint Technology Initiative) home page: http://www.cleansky.eu.
2. T.J. Lorenzen and V.L. Anderson, Design of Experiments, a no-name approach, Marcel Dekker, Inc., New York, USA, 1993.
3. A.I. Khuri and J.A. Cornell, Response Surfaces, Design and Analysis, Marcel Dekker, Inc., New York, USA, second edition, 1996.
4. d'Ippolito, R., El Masri, N., Hack, M., Tzannetakis, N., "Robustness optimization of suspension fatigue life using multibody simulation", paper submitted to Proc. NAFEMS World Congress 2009, Crete, Greece, June 16-19, 2009.
5. Noesis Solutions N.V., OPTIMUS Rev. 9 SL1, May 2010.
6. Goulos, I., Mohseni, M., Pachidis, V., d'Ippolito, R., Stevens, J., "Simulation Framework Development for Helicopter Mission Analysis", Proceedings of ASME Turbo Expo 2010, June 14-18, 2010, Glasgow, UK.
7. Goulos, I., Pachidis, V., Celis, C., d'Ippolito, R., Stevens, J., "Simulation Framework Development for Aircraft Mission Analysis", Proceedings of ASME Turbo Expo 2010, June 14-18, 2010, Glasgow, UK.