CLEANSKY GREEN ROTORCRAFT NOISE AND EMISSIONS BENEFITS – MAXIMIZING THE IMPACT OF NEW TECHNOLOGIES

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Abstract

This paper describes the work done by the Green Rotorcraft (GRC) Integrated Technology Demonstrator (ITD), the Sustainable And Green Engine (SAGE) ITD and the Technology Evaluator (TE) of the CleanSky Joint Technology Initiative (JTI). The GRC and SAGE ITD's are responsible for developing new (rotorcraft) technologies, whilst the TE has the distinctive role of assessing the environmental impact of these technologies at single flight (mission), airport and Air Transport System levels (ATS).

Besides the trade-off work already performed by each individual GRC subproject (GRCi), a need has emerged to perform trade-off studies for the complete rotorcraft with various technologies applied to the generic rotorcraft classes. The assessments reported here have been performed by using a GRC-developed multidisciplinary simulation framework called PhoeniX that comprises various computational modules. These modules include a rotorcraft performance code (EUROPA), an engine performance and emissions simulation tool (GSP or Turbomeca engine deck) and a noise prediction code (HELENA). PhoeniX can predict the performance of a rotorcraft along a prescribed 4D trajectory offering a complete helicopter mission analysis. Two helicopter classes have been examined, being a Single Engine Light (SEL) configuration for passenger transport missions and a Twin Engine Heavy (TEH) configuration for Oil & Gas missions. The results of this study illustrate the potential that incorporated technologies possess in terms of improving such performance metrics as fuel burn, and CO2 and NOx emissions.

SYMBOLS AND ABBREVIATIONS

4D	Four-dimensional
ABT	Active Blade Twist
ACARE	Advisory Council for Aeronautics Research in Europe
AGF	Active Gurney Flap
APU	Auxiliary Power Unit
ATC	Air Traffic Control
ATS	Air Transport System
AUM	All-Up Mass
B	Baseline
C	Conceptual
CFD	Computational Fluid Dynamics
CO2	Carbon Dioxide
CSJU	CleanSky Joint Undertaking
EUROPA	EUropean ROtorcraft Performance Analysis
GRC	Green RotorCraft
GRCi	GRC subproject
GSP	Gas-turbine Simulation Program
H/C	Helicopter
HCE	High Compression Engine
HELENA	HELicopter Environmental Noise Analysis
IFR	Instrument Flight Rules
ITD	Integrated Technology Demonstrator
JTI	Joint Technology Initiative
LMS	Leuven Measurement Systems
NLR	National Aerospace Laboratory
NOx	Nitrogen Oxides
PhoeniX	Platform Hosting Operational and Environmental Investigations for Rotorcraft
POB	Passive Optimized Blades
R	Reference
SAGE	Sustainable And Green Engine
SEL	Single Engine Light; Sound Exposure Level
SFC	Specific Fuel Consumption
TE	Technology Evaluator
TEH	Twin Engine Heavy
TEL	Twin Engine Light
TEM	Twin Engine Medium
VFR	Visual Flight Rules
WGS84	World Geodetic System 1984

1. INTRODUCTION

To minimise the future pollution impact of the aeronautics sector the CleanSky Programme[1], a consortium that harnesses the best skills and abilities of over eighty-six organizations representing leading European aircraft manufacturers, research and academic institutes, has been developed. The Programme's aim is to construct and operate aircraft incorporating new and innovative technologies that meet the emission and noise reduction targets set by the Advisory Council for Aeronautics Research in Europe (ACARE).

The object of the current work is to present the novel approach adopted by the Green Rotorcraft Integrated Technology Demonstrator (GRC-ITD) and the Technology Evaluator (TE), which enables the continual environmental impact assessment of the developing CleanSky technologies.

GRC's subproject GRC7 'Technology Evaluator for Rotorcraft' is the interface between the GRC-ITD and the TE. GRC7 prepares rotorcraft fleet data, puts together mathematical computer codes to predict the fuel burn, exhaust gas emissions and noise for rotorcraft flying typical mission profiles. GRC7 also defines generic rotorcraft models that represent all of the commercial rotorcraft operating in the Year 2000, plus concept designs for the Year 2020+ without and with CleanSky technology. TE analyses the environmental impact (noise and emissions), for which the Year 2000 helicopter fleet forms the baseline.

Four classes of baseline generic (turbine-powered) rotorcraft have been defined, based on number of engines and All-Up Mass (AUM):

- Single Engine Light (SEL)
- Twin Engine Light (TEL)
- Twin Engine Medium (TEM)
- Twin Engine Heavy (TEH)

GRC7 has developed the software tool named PhoeniX (Platform Hosting Operational & ENvironmental Investigations for Rotorcraft) for CleanSky, bringing together previously established software programs in a new simulation environment.

To establish the potential environmental benefits, the final assessment stage is to generate helicopter models that incorporate CleanSky technological developments into the baseline version, such as innovative rotor blades, improved airframe designs, integration of High-Compression (diesel) Engine technology and advanced electrical systems, drag reductions, elimination of the use of noxious hydraulic fluids and reduced fuel consumption.

The various GRC subprojects (GRCi's), as well as the SAGE ITD, are developing those new technologies. These developments are performed more or less individually, with little or no interrelation to other GRCi's. Each GRCi performs trade-off work to maximize the potential benefits of their technology and to choose an appropriate technology for each of the helicopter classes under consideration.

Besides the trade-off work already performed by each individual GRCi, a need has emerged to perform trade-off studies for the complete rotorcraft with various technologies. Given the uniqueness of possible rotorcraft configurations and the many operations that they can perform, no direct correlation can currently be safely assumed between the individual GRCi technology environmental targets and the final outcome of the synthesised models in the PhoeniX software platform. Moreover, the software platform includes helicopter missions that have been defined by the TE, which are representative for the year 2000 timeframe, thereby (possibly) not taking full advantage of the potential benefits of the new technologies. Therefore the trade-off work also includes the definition of (new or upgraded) future mission profiles that will be made possible thanks to those technologies.

In the trade-off studies attention is given to obtaining combinations of GRCi technologies in order to achieve the GRC environmental objectives. The results of the additional task will provide insight into the maximum environmental benefits that can be achieved by making use of the GRCi technologies. Because of the inclusion of (new or upgraded) future missions this goes beyond the current TE analysis. As such this study is seen as a necessary enhancement to the original GRC CleanSky objectives.

2. CLEANSKY GRC OBJECTIVES

The CleanSky JTI is one of the largest European research programmes ever. The objective of this unique public-private partnership is to speed up technological breakthrough developments and shorten the time to market for new solutions tested on Full Scale Demonstrators.

Speeding up new, greener design is essential to protect our environment. It should be kept in mind that aircraft have a 30-year service life, and that new aviation design takes more than a decade to develop. The accelerated research process that CleanSky offers represents an unprecedented opportunity for rapid progress in the introduction of green technology into aviation.

CleanSky will demonstrate and validate the technology breakthroughs that are necessary to make major steps towards the (overall) environmental goals sets by ACARE, to be reached in 2020:

- 50% reduction of CO2 emissions through drastic reduction of fuel consumption
- 80% reduction of NOx (nitrogen oxides) emissions
- 50% reduction of external noise
- A green product life cycle: design, manufacturing, maintenance and disposal/ recycling

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.

Green Rotorcraft has set a partial objective to be achieved by the year 2020 as resulting from CleanSky outputs of the Green Rotorcraft ITD and contributions from other ITDs, along with outputs of other already launched technology programmes. This objective 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 the ACARE targets, the GRC objectives are reported in Fig. 1.

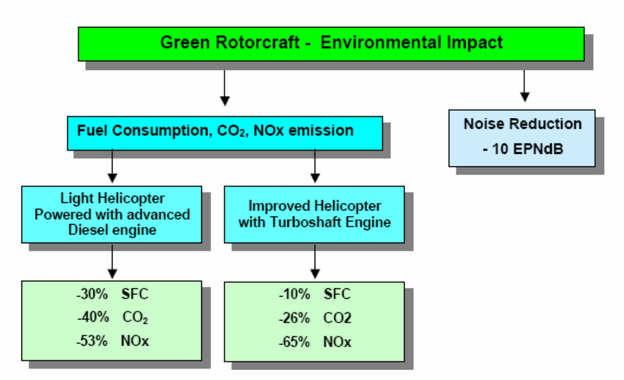

Figure 1 Expected Green Rotorcraft objectives

3. METHODOLOGY

For the purposes of assessing the environmental impact of the technologies that have been developed within the GRC ITD an integrated multidisciplinary framework has been created. This framework is called PhoeniX (Platform Hosting Operational & ENvironmental Investigations for Rotorcraft) and federates amongst others the following distinct computational tools:

- **EUROPA**: Rotorcraft flight mechanics code
- **GSP code** or **Turbomeca engine deck**: Gas turbine engine performance simulation and gas emissions calculation tools; GSP is gradually being replaced by the Turbomeca engine deck
- **HELENA**: Rotorcraft environmental noise analysis tool

These tools have been integrated into a single computational platform called OPTIMUS, which is a process integration simulation framework that establishes a proper workflow between the aforementioned computational tools. An architectural overview of the PhoeniX platform is illustrated in Figure 2.

European Rotorcraft Performance Analysis (EUROPA)

The EUROPA tool is a helicopter flight mechanics code, designed to calculate helicopter steady state (trim) and dynamic (manoeuvre) performance. It is ideally suited to determine (optimized) take-off and landing flight paths. The code was developed and validated in the European RESPECT project[2]. A version dedicated to tilt rotor aircraft was developed in the European NICETRIP project[3].

The flight mechanics simulation generates a helicopter's trajectory in order to analyse 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 assess 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, altitude, tip path plane angles etc. as a function of time. EUROPA provides this information to the other tools for noise and fuel burn/ gas emissions estimations along each segment of the trajectory.

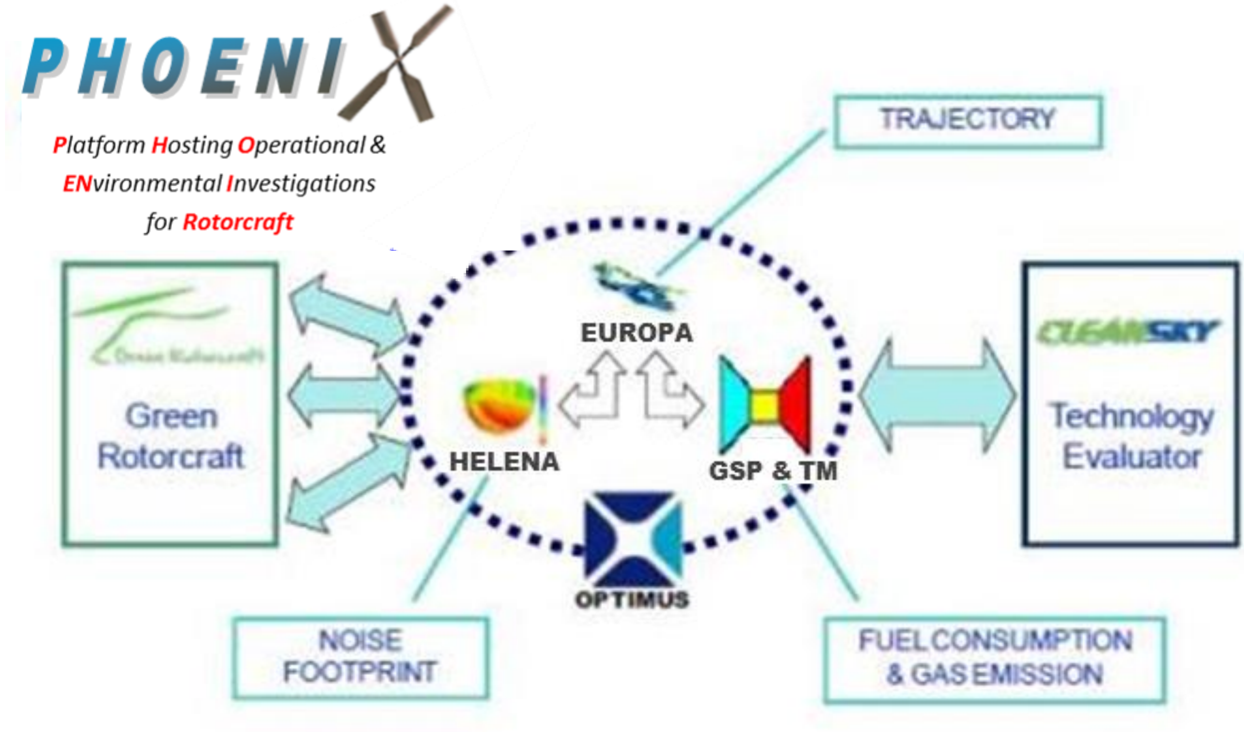

Figure 2 Architectural overview of PhoeniX platform

Gas-turbine Simulation Program (GSP)

The next tool integrated in the PhoeniX platform is the Gas turbine Simulation Program (GSP). GSP is an in-house tool developed by NLR to simulate gas turbine thermodynamic cycles for engine performance (fuel consumption, power output) and exhaust gas emissions. GSP implements a zero dimensional engine model (with a one dimensional combustion chamber 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.

Within the PhoeniX framework, GSP is used to compute the gas emissions, the power available and the fuel burn in a coupled simulation with the EUROPA code. In this case, GSP retrieves the power required and the atmospheric data from EUROPA and also uses the engine data from its database. With these data at each instant in time, GSP determines the fuel burn (used for mission mass calculation) and generates exhaust gas emissions.

Turbomeca engine deck

As an alternative to the GSP code, engine decks developed by Turbomeca have been introduced. Safran's Turbomeca division is the leading engine manufacturer for helicopters. Their engine decks represent average engines for each generic rotorcraft class and these decks estimate steady-state engine performance, fuel burn and exhaust gas emissions.

Within the PhoeniX framework, the Turbomeca engine deck behaves the same as GSP in that it is used to compute the fuel burn, the gas emissions and the power available in a coupled simulation with the EUROPA code. However in addition, the conceptual model is enhanced by a more accurate representation of the SAGE5 innovative low NOx combustion technology.

Helicopter Environmental Noise Analysis (HELENA)

In order to assess the noise footprint of the flown trajectory computed by EUROPA, the HELENA tool is being used. The HELENA tool was developed within the FRIENDCOPTER[4] 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 also take into account distance (short and long), wind effects, atmospheric absorption effects, and ground reflection and shielding effects. HELENA has been validated with dedicated flight tests. As a result of the analysis of the trajectory data received from EUROPA, HELENA computes the noise level at the ground for each trajectory segment. In particular, HELENA computes the noise levels for a variety of noise metrics.

OPTIMUS Simulation Framework Toolkit

The federation of the aforementioned simulation tools has been carried out with OPTIMUS[5], provided by LMS Intl. and NOESIS Solutions. 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 framework establishes a proper workflow between the aforementioned computational tools. It allows the execution of the multidisciplinary workflow for each helicopter mission profile and helicopter class defined. Each mission is defined by a set of flight and helicopter conditions that can be changed for every experiment and which are identified by a set of values of the input parameters.

PhoeniX assessment methodology

A typical assessment of a rotorcraft's noise and exhaust gas emissions over a single mission and for a given set of inputs involves the following steps:

- The EUROPA code accepts the helicopter data, the mission profile, and the flight and atmosphere conditions as input. Based on these user defined conditions, the EUROPA code calculates a flight path divided into different segments. For each segment, the EUROPA code returns the helicopter position, the time to reach that position, the helicopter attitude and tip path plane angles, the power required and the atmospheric conditions.
- The GSP code and Turbomeca engine deck are coupled inside EUROPA. For each time segment calculated by EUROPA, the engine code retrieves the atmospheric conditions (pressure and temperature) and the power required. It then uses this information to calculate the fuel burn and the emissions' quantity of CO2, NOX and the like produced during every segment. After the successful convergence of the mission fuel by EUROPA and GSP/Turbomeca, OPTIMUS extracts these results and post processes them to produce the total quantities of fuel burnt and polluting gases generated during the entire trajectory.
- After the successful convergence of the mission fuel by EUROPA and GSP/ Turbomeca, OPTIMUS also automatically reads EUROPA's trajectory output file and passes this data to HELENA in the appropriate format in order to perform the noise assessment. HELENA then determines the noise footprints for the given flight conditions. When the levels of three characteristic noise metrics have been calculated for each segment, OPTIMUS extracts the results and collects the data needed for further analyses.

It is worth pointing out that EUROPA as a comprehensive rotorcraft flight mechanics code works in a rather modular fashion. To be more specific, the performances of individual rotorcraft components such as the main rotor, tail rotor, fuselage, empennage and the engine are calculated in an integrated manner. The ultimate goal is to provide the performance of a rotorcraft during its specific mission. In PhoeniX, it is possible to define a complete mission in terms of WGS 84 coordinates. Thus, a realistic mission with a complete flight trajectory can be designed and the helicopter's performance can be assessed during all possible flight segments such as hover, take off, cruise, loiter, descent, landing and idle.

Helicopter Classes and Configurations

The main goal of the CleanSky TE is to assess and compare three different helicopter configurations which are the Year 2000 Baseline, the Year 2020 Reference and the Year 2020 Conceptual with CleanSky benefits. The Baseline configurations correspond to existing technology and concepts which were built until the year 2000. Reference and Conceptual configurations correspond to projected technologies up until the year 2020 without and with CleanSky benefits respectively.

The technological benefits which are acquired through the research done within the GRC ITD and within other ITDs are implicitly expressed into the specifications of the individual helicopter components. For example, a Conceptual helicopter may have a reduced drag coefficient compared to a Reference and Baseline configuration. These changes in such coefficients as the drag coefficient will result to differences in fuel burn, in CO2 and NOx gas emissions, and in noise emitted across the three helicopter configurations.

4. CLEANSKY TECHNOLOGIES

The various GRCi's and also the SAGE ITD are developing new technologies. Those technologies are further detailed in the following paragraphs.

4.1. GRC1 Innovative rotor blades

The objective of GRC1 is the development of active and passive technologies to provide the greatest possible reduction in rotor noise and fuel consumption. Adopted technologies are:

- Passive Optimized Blades (POB); the blade's geometry and aerodynamic profile section have been optimised with the aim of achieving significant performance and acoustic benefits
- Active Gurney Flaps (AGF); for performance benefits these can be used to delay the onset of retreating blade stall at high speeds, and to reduce collective pitch requirements at cruise speeds; for acoustic benefits these can facilitate a reduction in main rotor speed, with an accompanying reduction in main rotor thickness noise
- Active Blade Twist (ABT); the active twist system would be used for only one benefit at a given time: for example performance benefits will be possible in helicopter cruise flight, while acoustic benefits will be obtained on approach to landing

4.2. GRC2 Reduced drag of airframe and non-lifting rotating parts

The objective of GRC2 is the reduction of emissions and noise through rotorcraft drag reduction and airframe optimisation. Adopted technologies are:

- Rotor hub/mast fairing drag reduction
- Fuselage drag reduction
- Improved engine installation
- Optimised airframe design

4.3. GRC3 Integration of innovative electrical systems

The objectives of GRC3 are:

- Removal of hydraulic fluid
- Deletion of engine bleed air circuit
- Weight reduction
- Reduced maintenance burden for operators

Adopted technologies are:

- Efficient electrical generation, conversion and distribution (generic for small aircraft)
- Electromagnetic actuators for helicopter flight control (ground testing)
- Efficient power generation and control for piezoelectric actuation, esp. active blades
- Electrically driven tail rotor (concept studies)

4.4. GRC4 Installation of a high-compression engine on a light helicopter

The objectives of GRC4 are:

- Lower fuel consumption by a minimum of 30%, and up to 50% depending on duty cycle
- Reduction of emissions up to -40% for CO2 and -50% for Nox
- Increased mission range/endurance with the same amount of fuel
- Reduced direct operating costs
- Improved rotorcraft performance in hot and high conditions
- To integrate the engine minimising the potential adverse effects of weight penalty, vibration and cooling system

The consortium TEOS Powertrain Engineering/ Austro Engine GmbH has developed a 440 shp High-Compression Engine (HCE) that uses regular kerosene fuel (or bio-diesel). This engine is targeted at the Single Engine Light (SEL) helicopter.

4.5. GRC5 Environmentally-friendly flight path

The objectives of GRC5 are:

- Noise footprint and noise impact reduction
- Minimise fuel consumption and gas emission

Adopted technologies are:

- IFR and VFR approach and departure procedures
- Low level VFR and IFR en route navigation
- Rotorcraft specific shorter routes to minimise fuel consumption and gas emission

4.6. GRC6 Eco-design demonstrators for rotorcraft

The objective of GRC6 is to demonstrate eco-friendly life cycle processes for specific helicopter components. Adopted technologies are:

- Use of composite thermoplastic structures
- Banning dangerous materials like Chrome-6 and Cadmium for the protection, touch up and painting of gearbox housings and transmission shafts

- Reducing energy consumption and emission of volatile organic components during production and repair of gearbox housings and transmission shafts

4.7. SAGE5 Turboshaft engine demonstrator

The objective of SAGE5 is to provide the necessary technologies for the development of a new engine family equipping helicopter classes with a take-off weight from 3 tons (single-engine) to 6 tons (twin-engine). The technologies to be demonstrated will deliver improved specific fuel consumption, and reduced noise and exhaust gas emissions. The validation work regarding the innovative low NO_x combustion technology is still ongoing. Therefore it is to be noted that all NOx results are preliminary values.

5. TRADE-OFF STUDIES

In the previous chapter the individual technologies have been detailed. Further to the analyses carried out by the TE (analysing the impact of all technologies together, and for default missions that do not change when going from Baseline to Reference to Conceptual helicopter), GRC7 has performed a more detailed study, in which the impact of individual technologies has been assessed. The results of the latter analyses are quantified in the underlying chapter. When applied to the helicopter all of those individual technologies are in some way interrelated. E.g. a reduction in drag area has a direct impact on power required and thus on fuel consumption, but also on the engine that will be installed. The combined effect is a reduction in helicopter All-Up Mass (AUM), which then will affect the rotor dimensions. An iterative process is required to size such a helicopter for each applied technology.

Assessing the impact of individual technologies is not an easy task. Ideally one would start off from the Year 2020 Reference helicopter and add the individual technologies one at a time. Then, for each added technology, the complete helicopter would have to be re-defined, including a proper engine class. And also a complete set of noise hemispheres would need to be derived for each applied technology or combinations of technologies. Such an approach would require far too much effort. Therefore a different approach has been adopted, which still gives a good indication of the individual technologies' impact. As a baseline the Year 2020 Reference helicopter configuration will be used, to which individual (or combined) technologies have simply been added, without fully redefining the helicopter. Noise footprint calculations have been carried out for a limited number of configurations.

So far the technology impact has been assessed for the following two generic rotorcraft classes:

- Single Engine Light (SEL) with AUM ≤ 4 metric tons
- Twin Engine Heavy (TEH) with AUM ≥ 8 metric tons

These two classes represent 57% and 10% of the Year 2000 worldwide helicopter fleet of more than 16600 individual helicopters (Fig. 3).

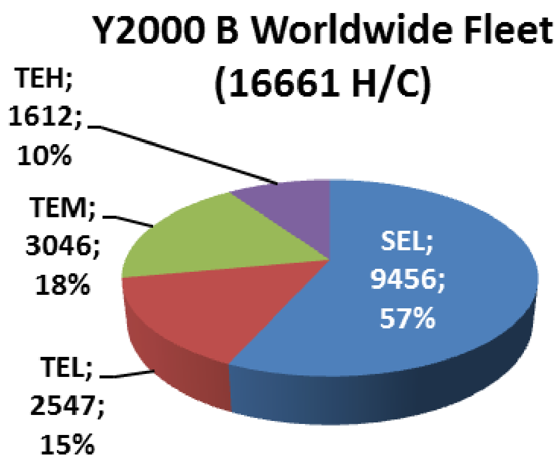

Figure 3 Year 2000 worldwide helicopter fleet

5.1. Single Engine Light (SEL) helicopter

This chapter quantifies the impact of the individual technologies that have been implemented on the Year 2020 Conceptual Single Engine Light helicopter (SEL-C):

- Passive Optimized Blades: estimated weight delta 0 kg, estimated electrical power 0 kW
- Drag reduction for rotor head (-3.5 %), fuselage (-7.5 %) and skids (-7.2%)
- Integration of innovative electrical systems: estimated weight delta -5 kg
- Structural weight saving campaign: estimated weight delta -10.5 kg
- New engines with reduced fuel burn and NOx emission

NB: although the High Compression Engine (HCE) has been implemented on a dedicated variant of the SEL helicopter, this technology is not included in these trade-off studies; the HCE is heavier than a turboshaft engine, but has a lower fuel consumption; a helicopter equipped with HCE is at a disadvantage for shorter ranges, and at an advantage for longer ranges; therefore the HCE-equipped helicopter is targeted at different mission scenarios, thus impeding a direct comparison.

The following cases have been analysed:

- SEL-R
- SEL-R with Passive Optimized Blades (POB)
- SEL-R with reduced drag for rotor hub, fuselage, skids
- SEL-R with 15.5 kg weight reduction
- SEL-R with SEL-C engine model
- SEL-C

5.1.1. Default passenger mission

The initial analysis has been carried out for the default SEL passenger transport mission (Fig. A.1). The helicopter takes off from Hannover Airport (Germany) to pick up four passengers from a secondary location. It subsequently transfers them to the Garbsen Hotel and then transits back to Hannover Airport where it originated from. The selected route has not been restrained by noise abatement procedures. The mission endurance is ½ hour, whereas the cruise speed and cruise altitude are 120 kts and 1500 ft resp.

The results for the analysed cases are shown in Table 1. Please bear in mind that the data for individual technologies cannot be shared for proprietary reasons. Therefore the cases are listed in order of increasing benefit, which not necessarily is the same order as listed before.

Case	Fuel (kg)	Δ fuel (%)	CO2 (kg)	Δ CO2 (%)	NOx (kg)	Δ NOx (%)
SEL-R	38.4	0%	120.1	0%	0.175	0%
Case #	38.3	-0.3%	119.9	-0.2%	0.174	-0.5%
Case #	38.1	-0.8%	119.1	-0.8%	0.172	-1.6%
Case #	37.1	-3.4%	115.9	-3.5%	0.161	-7.9%
Case #	34.7	-9.7%	108.5	-9.7%	0.100	-42.8%
SEL-C	32.7	-14.9%	102.2	-14.9%	0.085	-51.2%

Table 1 SEL trade-off results for passenger mission

Figure 4 shows all results in a bar chart, again in order of increasing benefit.

5.1.2. Discussion of results

The default passenger mission does not use the full potential of the SEL helicopter, e.g. because the mission is rather short and flown at moderate mass. Looking at the adopted technologies one can discern the following trends:

- The Passive Optimized Blades have the largest benefit in hover and a somewhat smaller benefit in high speed flight
- The drag reduction has the largest benefit in high speed flight
- The weight reduction has a small impact for this specific mission profile, which is largely flown in cruising conditions
- The benefit of the new engines is an overall benefit, not really depending on the mission profile

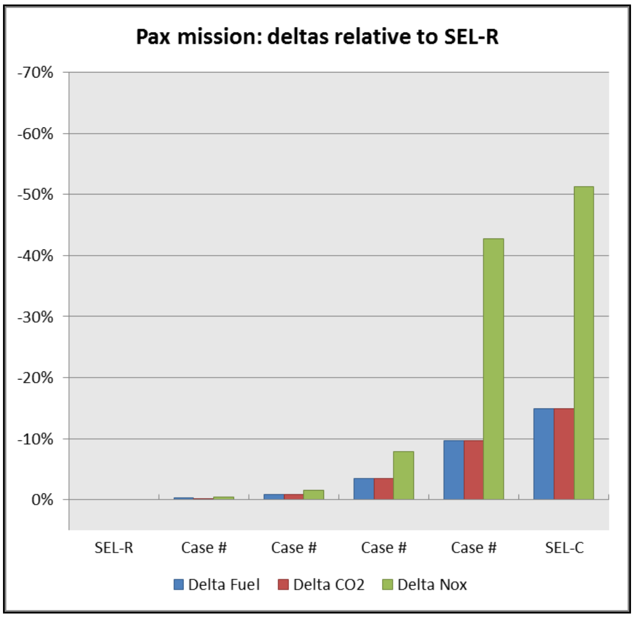

Figure 4 SEL trade-off results for passenger mission

With the foregoing in mind two new, more demanding, mission profiles have been defined for the SEL helicopter that should show a larger benefit due to the adopted technologies. The first one is a fire suppression mission during which a considerable part of the mission profile is flown in hover or low speed. This will merit the use of Passive Optimized Blades. The second mission is a long distance passenger transport mission flown at high cruising speed. This will merit the use of the drag reduction and, to a lesser extent, the use of Passive Optimized Blades. Each of these missions and their results is further described in the next two sections.

5.1.3. More demanding mission '1'

The fire suppression mission (Fig. A.2) is based on the default fire suppression mission defined for the Twin Engine Medium (TEM) helicopter, but with the mission equipment mass and the water mass halved to fit with the SEL helicopter. The helicopter takes off from Rome Ciampino Airport in Italy. The helicopter will transit at high speed towards a water collection point ('Riserva Naturale Monterano') which is nearest to the fire incident location. There the water bucket is filled, the helicopter flies to the location of the fire and drops the water on the fire. The helicopter flies various sorties between the water collection point and the fire zone. Noise abatement procedures have not been imposed for the particular trajectory as well as no ATC constraints. Finally, the helicopter will fly back to and land at the original helipad. The mission duration is about 2½ hours.

The results for the analysed cases are shown in Table 2 (in order of increasing benefit).

Case	Fuel (kg)	Δ fuel (%)	CO2 (kg)	Δ CO2 (%)	NOx (kg)	Δ NOx (%)
SEL-R	227.4	0%	711.3	0%	1.177	0%
Case #	226.6	-0.4%	708.7	-0.4%	1.168	-0.8%
Case #	223.7	-1.6%	699.8	-1.6%	1.138	-3.3%
Case #	219.7	-3.4%	687.1	-3.4%	1.097	-6.8%
Case #	201.0	-11.6%	628.8	-11.6%	0.551	-53.2%
SEL-C	192.1	-15.5%	600.9	-15.5%	0.496	-57.9%

Table 2 SEL trade-off results for fire suppression mission

Figure 5 shows all results in a bar chart (in order of increasing benefit).

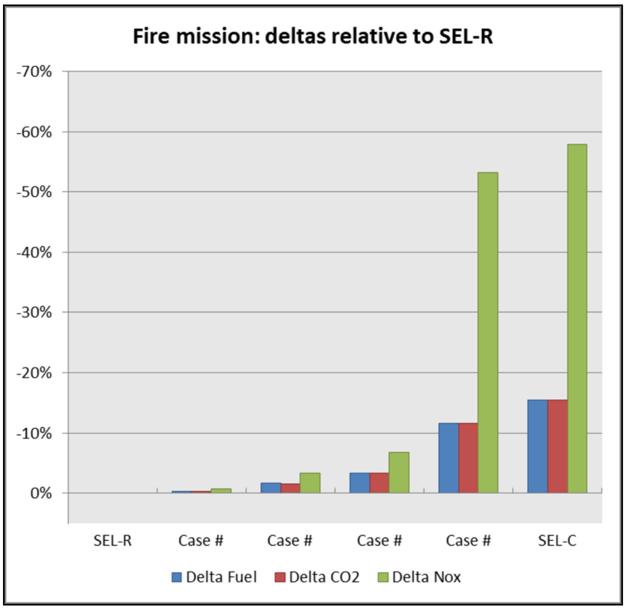

Figure 5 SEL trade-off results for fire suppression mission

Comparing Figures 4 and 5 clearly shows that there is a slight increase in fuel and CO2 benefits. The benefit on NOx production for one of the technologies has increased by up to 10 percent points and for the combined technologies (SEL-C) has increased by about 7 percent points.

5.1.4. More demanding mission '2'

The long distance, high speed passenger transport mission (Fig. A.3) is based on the default Hot and High mission defined for the High Compression Engine (HCE) helicopter. The helicopter takes off from Hannover Airport (Germany) with 2 passengers. It then climbs to 2000 ft under ISA conditions and transits at 125 kts cruising speed to the northern part of the Netherlands, before returning back to the original helipad at Hannover Airport. The mission duration is about 2 hrs.

The results for the analysed cases are shown in Table 3 (in order of increasing benefit).

Case	Fuel (kg)	Δ fuel (%)	CO2 (kg)	Δ CO2 (%)	NOx (kg)	Δ NOx (%)
SEL-R	232.3	0%	726.5	0%	1.453	0%
Case #	232.2	0%	726.3	0%	1.452	0%
Case #	228.4	-1.6%	714.6	-1.6%	1.413	-2.7%
Case #	210.3	-9.5%	657.8	-9.5%	1.222	-15.9%
Case #	209.5	-9.8%	655.1	-9.8%	0.660	-54.6%
SEL-C	185.7	-20.1%	580.8	-20.1%	0.447	-69.2%

Table 3 SEL trade-off results for fast/far mission

Figure 6 shows all results in a bar chart (in order of increasing benefit).

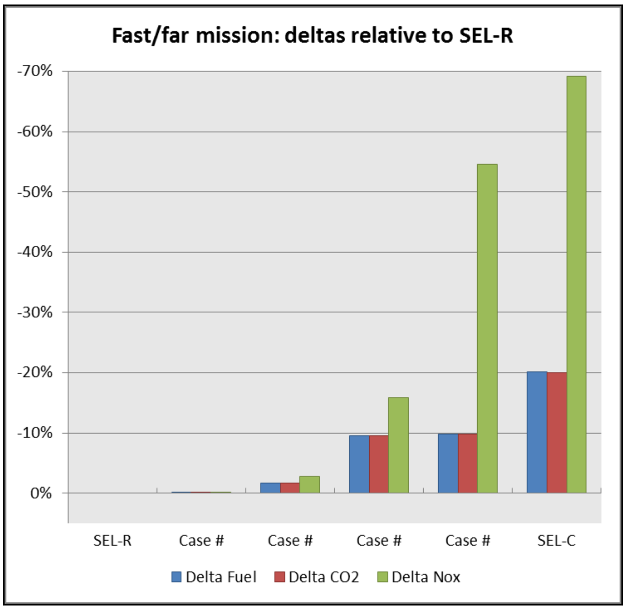

Figure 6 SEL trade-off results for fast/far mission

When comparing Figures 4 and 6 a clear increase in fuel and CO2 benefits for one of the technologies can be noted. The benefits on NOx production for two of the technologies have increased by 7-12 percent points. For the combined technologies (SEL-

C) the benefits for all three parameters has increased, for NOx even by about 18 percent points.

5.1.5. Noise trade-off study

As part of their work GRC5 have established noise-optimized approach procedures for the various helicopter classes, the so-called Low Noise Procedures (LNPs). SEL-B and SEL-R normally fly the reference (baseline) approach, whereas SEL-C flies the LNP approach. Both approaches (reference and LNP) start in level flight at a height of 1000ft and a speed of about 115kts (see Fig. 7). The reference approach is flown at about 65kts with a 6 degree descent angle from 1000ft down to the flare point at 150ft, whereas the LNP approach uses a 9 degrees descent angle from 1000ft down to 150 ft. From the flare point down to the landing point the forward and vertical speed components are gradually reduced. The final descent from a height of 40ft till touchdown is flown vertically.

As elucidated in the beginning of chapter 5 a full noise trade-off analysis for every single technology is not possible due to the lack of relevant noise hemispheres. Therefore a different approach has been adopted here, in which noise footprint plots have been derived for the approach and landing for:

- SEL-R with reference approach (Fig. 8)
- SEL-C with reference approach (Fig. 9)
- SEL-C with LNP approach (Fig. 10)

In all figures the helicopter approaches from the left and lands towards the right (landing point at coordinates Xac=0, Yac=0).

Finally, Table 4 shows the 85 SEL (dBA) iso-noise contour areas for the three combinations.

Combination	Area (km^2)	Δ Area (%)
SEL-R, Reference Approach	1.17	0%
SEL-C, Reference Approach	0.27	-76.9%
SEL-C, Low Noise Procedure Approach	0.10	-91.5%

Table 4 SEL noise analysis, 85 SEL (dBA) iso-noise contour areas

Moving from Fig. 8 to Fig. 9 there is a considerable reduction in noise levels, which is mainly attributable to the use of a lower rotor rpm on SEL-C. Moving from Fig. 9 to Fig. 10 the differences stem from the adoption of a steeper approach flight path angle during the LNP approach.

For SEL-C with LNP approach there is a slightly larger 80 SEL (dBA) area on the left of the figure, which is due to the longer level flight phase. For this procedure the descent phase starts closer to the landing point (at 2600m instead of 3300m for the reference approach). For the LNP approach all noise contour areas closer to the landing point are smaller, indicating the noise benefit for this LNP approach.

5.1.6. Summary of SEL trade-off study

Depending on the mission profile the potential reductions due to the incorporation of individual technologies roughly vary from:

- Fuel burn/CO2 0 to 12%
- NOx 0 to 55%

with the more demanding missions showing the largest benefits.

The potential reductions for the combined technologies amount up to:

- Fuel burn/CO2 15 to 20%
- NOx 51 to 69%

The fuel burn/CO2 benefit when going from the Baseline to Reference helicopter is 4.8%; this value should be added to the above results, thereby getting close to the GRC objectives. It is to be noted that the above NOx results are preliminary values.

Adopting the LNP approach and landing on SEL-C reduces the 85 SEL (dBA) iso-noise footprint contour area by nearly 92% when compared to the reference approach.

5.2. Twin Engine Heavy (TEH) helicopter

This chapter quantifies the impact of the individual technologies that have been implemented on the Year 2020 Conceptual Twin Engine Heavy helicopter (TEH-C):

- Passive Optimized Blades (POB): estimated weight delta 0 kg, estimated electrical power 0 kW
- Active Gurney Flap (AGF): estimated weight delta +26.5 kg, estimated electrical power +1.6 kW; NB in this case the AGF is only used as a means of gaining performance benefits
- Drag reduction for fuselage (-6.0 %) and rotor head (-16.66 %)
- Integration of innovative electrical systems: estimated weight delta -91 kg
- Structural weight saving campaign: estimated weight delta -14 kg
- New engines with reduced fuel burn and NOx production

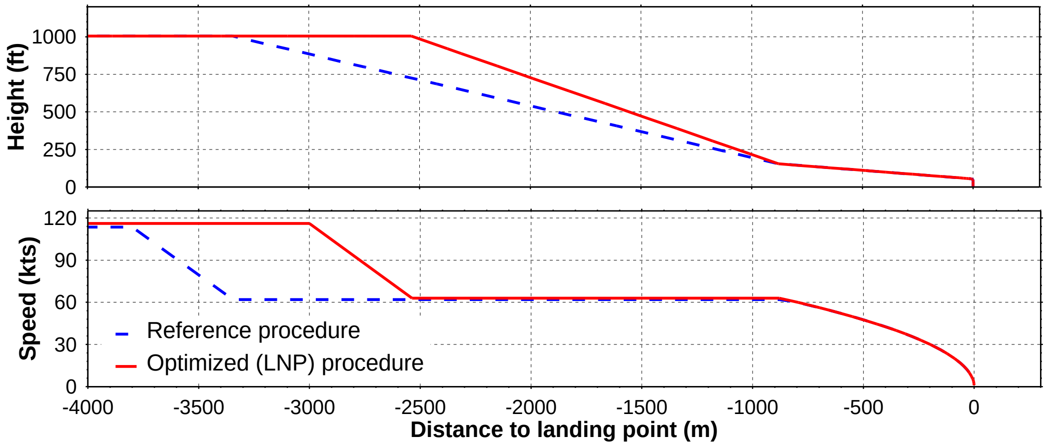

Figure 7 Height-Speed profiles for reference and optimized (LNP) approach procedures

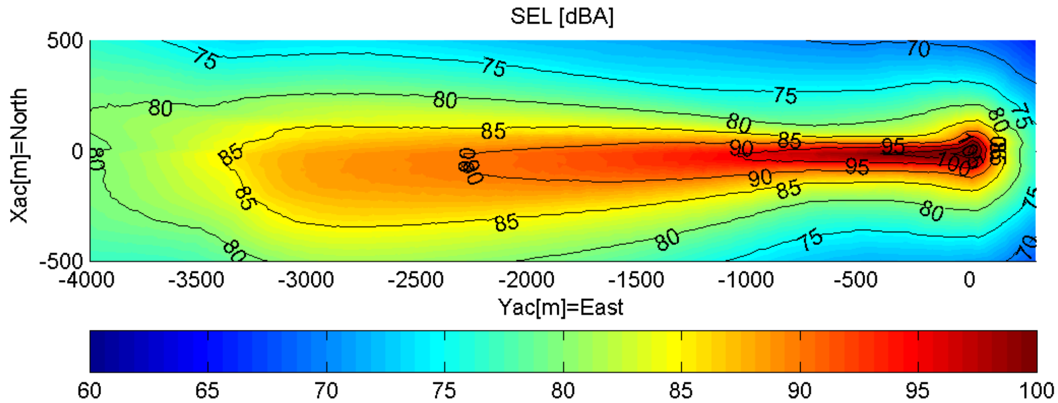

Figure 8 Noise footprint plot for SEL-R with reference approach

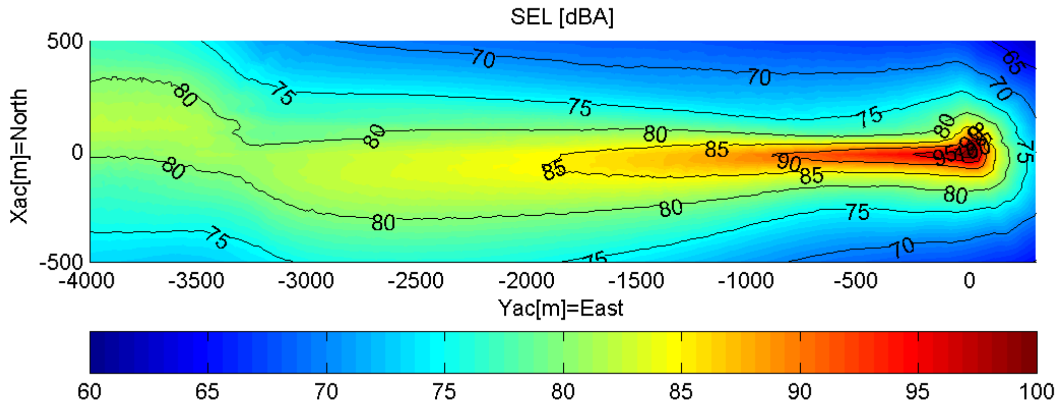

Figure 9 Noise footprint plot for SEL-C with reference approach

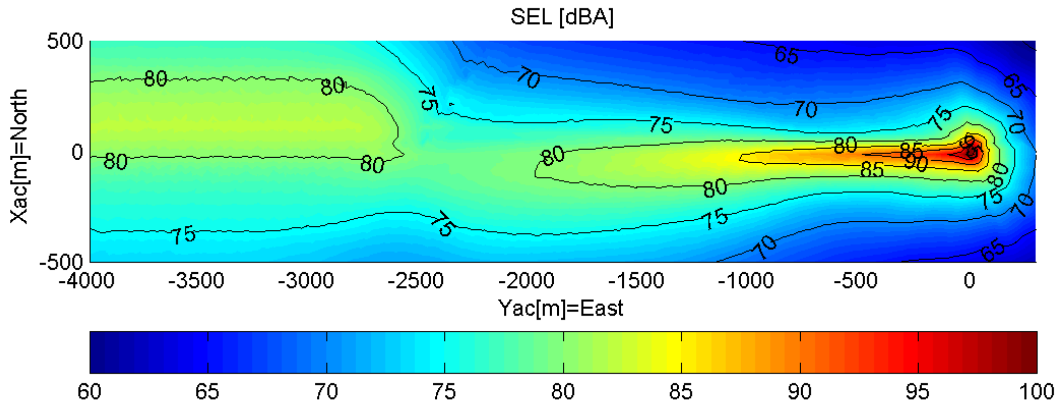

Figure 10 Noise footprint plot for SEL-C with LNP approach

The following cases have been analysed:

- TEH-R
- TEH-R with Passive Optimized Blades (POB)
- TEH-R with Active Gurney Flap (AGF)
- TEH-R with reduced drag for rotor hub and fuselage
- TEH-R with 105 kg weight reduction
- TEH-R with TEH-C engine model
- TEH-C

No noise footprint calculations have been carried out for TEH.

5.2.1. Default oil/gas mission

The initial analysis has been carried out for the default TEH oil/gas mission (Fig. A.4). This mission has been based on the potential of the Year 2000 TEH Baseline helicopter. The helicopter will take off from Den Helder Airport in the Netherlands. It will transit towards the specific oil platforms L04-A and L04-B which are located in the south continental shelf of the Netherlands on the North Sea. The helicopter will carry personnel and personal baggage and drops them off after landing at each of the two designated oil platforms. Subsequently the helicopter will return back to Den Helder Airport. Noise considerations as well as ATC constraints have not been taken into account for this particular route. The mission endurance is 1½ hour, whereas the cruise speed and cruise altitude are 120 kts and 3000 ft resp.

The results for the analysed cases are shown in Table 5 (in order of increasing benefit).

Case	Fuel (kg)	Δ fuel (%)	CO2 (kg)	Δ CO2 (%)	NOx (kg)	Δ NOx (%)
TEH-R	684.1	0%	2161.6	0%	4.656	0%
Case #	684.8	0.1%	2163.9	0.1%	4.668	0.3%
Case #	682.7	-0.2%	2157.1	-0.2%	4.628	-0.6%
Case #	679.4	-0.7%	2146.6	-0.7%	4.585	-1.5%
Case #	674.2	-1.4%	2130.3	-1.4%	4.468	-4.0%
Case #	615.0	-10.1%	1943.3	-10.1%	2.503	-46.2%
TEH-C	605.8	-11.4%	1914.2	-11.4%	2.478	-46.8%

Table 5 TEH trade-off results for oil/gas mission

Figure 11 shows all results in a bar chart (in order of increasing benefit).

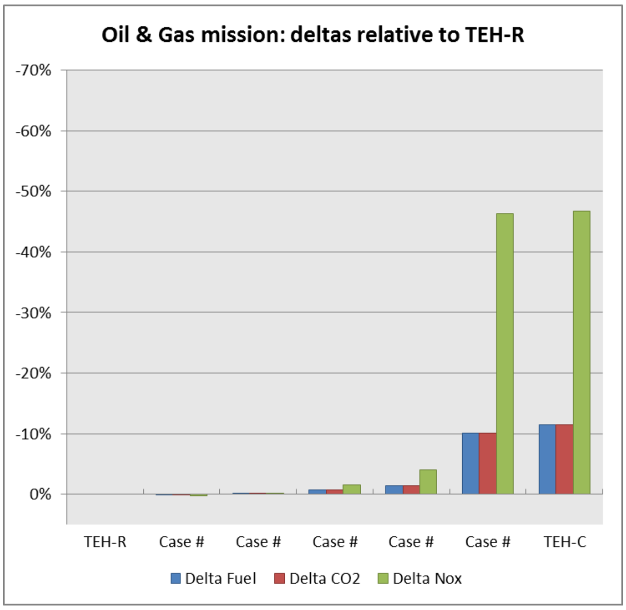

Figure 11 TEH trade-off results for oil/gas mission

5.2.2. Discussion of results

The default oil/gas mission does not use the full potential of the TEH helicopter, because the mission is not so demanding from a perspective of mass, flight conditions and duration. Looking at the adopted technologies one can discern the following trends:

- The Passive Optimized Blades have the largest benefit in hover (which is normally not the flight condition in which the TEH will spend a lot of time) and a somewhat smaller benefit in high speed flight
- The Active Gurney Flap has the largest benefit at high rotor thrust and in high speed flight
- The drag reduction has the largest benefit in high speed flight
- The weight reduction has a small impact for this specific mission profile, which is largely flown in cruising conditions
- The benefit of the new engines is an overall benefit, not really depending on the mission profile

With the foregoing in mind a new, more demanding, mission profile has been defined for the TEH helicopter that should show a larger benefit due to the adopted technologies.

In order to maximize the benefit of the AGF and of the reduced drag levels, flight conditions with high thrust coefficient and high advance ratio are required. Therefore a long-range passenger transport mission under hot and high conditions has been defined for this analysis. This mission and its results are further described in the next section.

5.2.3. More demanding mission

The long range passenger transport mission (Fig. A.5) starts from Rome Airport and then flies to Siena, Rimini, Pescara and back to Rome, crossing the Apennine Mountains twice. Payload is 2510 kg, outside air temperature is ISA+25°C, cruising altitude is 8000 ft, and cruising speed is 140-150 kts. The mission duration is close to 3 hours.

It is to be noted that the take-off and landing phases in this 'more demanding' mission are not flyable due to a shortage in power available. Therefore those flight phases are not included in the mission profile for this theoretical exercise (although the climb and descent phases in forward flight are included).

The results for the analysed cases are shown in Table 6 (in order of increasing benefit).

Case	Fuel (kg)	Δ fuel (%)	CO2 (kg)	Δ CO2 (%)	NOx (kg)	Δ NOx (%)
TEH-R	1511.6	0%	4776.8	0%	13.937	0%
Case #	1502.3	-0.6%	4747.2	-0.6%	13.763	-1.2%
Case #	1493.7	-1.2%	4720.2	-1.2%	13.625	-2.2%
Case #	1450.0	-4.1%	4581.9	-4.1%	12.869	-7.7%
Case #	1439.6	-4.8%	4549.1	-4.8%	12.690	-8.9%
Case #	1391.3	-8.0%	4396.5	-8.0%	6.632	-52.4%
TEH-C	1276.8	-15.5%	4034.6	-15.5%	4.805	-65.5%

Table 6 TEH trade-off results for long range mission

Figure 12 shows all results in a bar chart (in order of increasing benefit).

Comparing Figures 11 and 12 clearly shows that there are increases in fuel, CO2 and NOx benefits for several of the technologies by up to 6 percent points. For the combined technologies (TEH-C) the increase in fuel and CO2 benefits is about 4 percent points and in NOx 20 percent points.

5.2.4. Summary of TEH trade-off study

Depending on the mission profile the potential reductions due to the incorporation of individual technologies roughly vary from:

- Fuel burn/CO2 0 to 10%
- NOx 0 to 52%

with the more demanding missions showing the largest benefits.

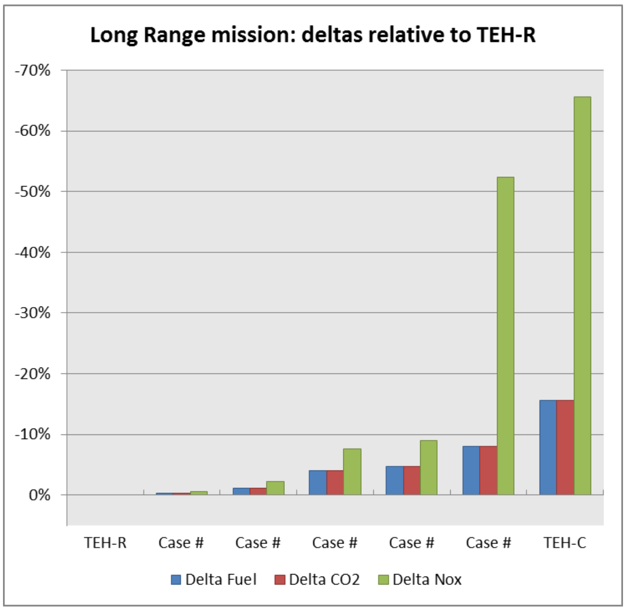

Figure 12 TEH trade-off results for long range mission

The potential reductions for the combined technologies amount up to:

- Fuel burn/CO2 11 to 16%
- NOx 47 to 66%

The fuel burn/CO2 benefit when going from the Baseline to Reference helicopter is 10.2 %; this value should be added to the above results, thereby getting close to the GRC objective. It is to be noted that the above NOx results are preliminary values.

6. CONCLUSIONS

Trade-off studies have been performed for complete rotorcraft with various implemented technologies, for default mission profiles as well as for more demanding mission profiles (taking maximum advantage of the potential of those technologies). The study results show that the adoption of new technologies has a great potential of reducing important metrics like fuel burn, CO2 and NOx gas emissions and noise footprints between Reference and Conceptual configurations. The reductions are consistent throughout, with larger benefits being possible for more demanding missions.

For the Single Engine Light (SEL) helicopter in the default passenger mission reductions of up to 15% in fuel burn and CO2 emissions are possible, and up to 51% in NOx emissions. For more demanding missions these numbers can increase to 20% and 69% respectively. The adoption of the Low Noise Procedure (LNP) approach reduces the 85 SEL (dBA) iso-noise footprint contour area by nearly 92%

when compared to the reference approach.

For the Twin Engine Heavy (TEH) helicopter in the default oil & gas mission these numbers amount to 11% (fuel/CO_2) and 47% (NOx) resp., whereas for the more demanding mission reductions up to 16% and 66% resp. are possible.

It is to be noted that these results show the benefits between a Year 2020 Reference helicopter without and a Year 2020 Conceptual helicopter with new technologies. Additional benefits are found when going from the Y2000 Baseline helicopter to the Y2020 Reference helicopter without new technologies. Due to the current status of the SAGE5 innovative low NOx combustion technology all NOx results are preliminary.

7. ACKOWLEDGEMENTS

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APPENDIX A: MISSION PROFILES

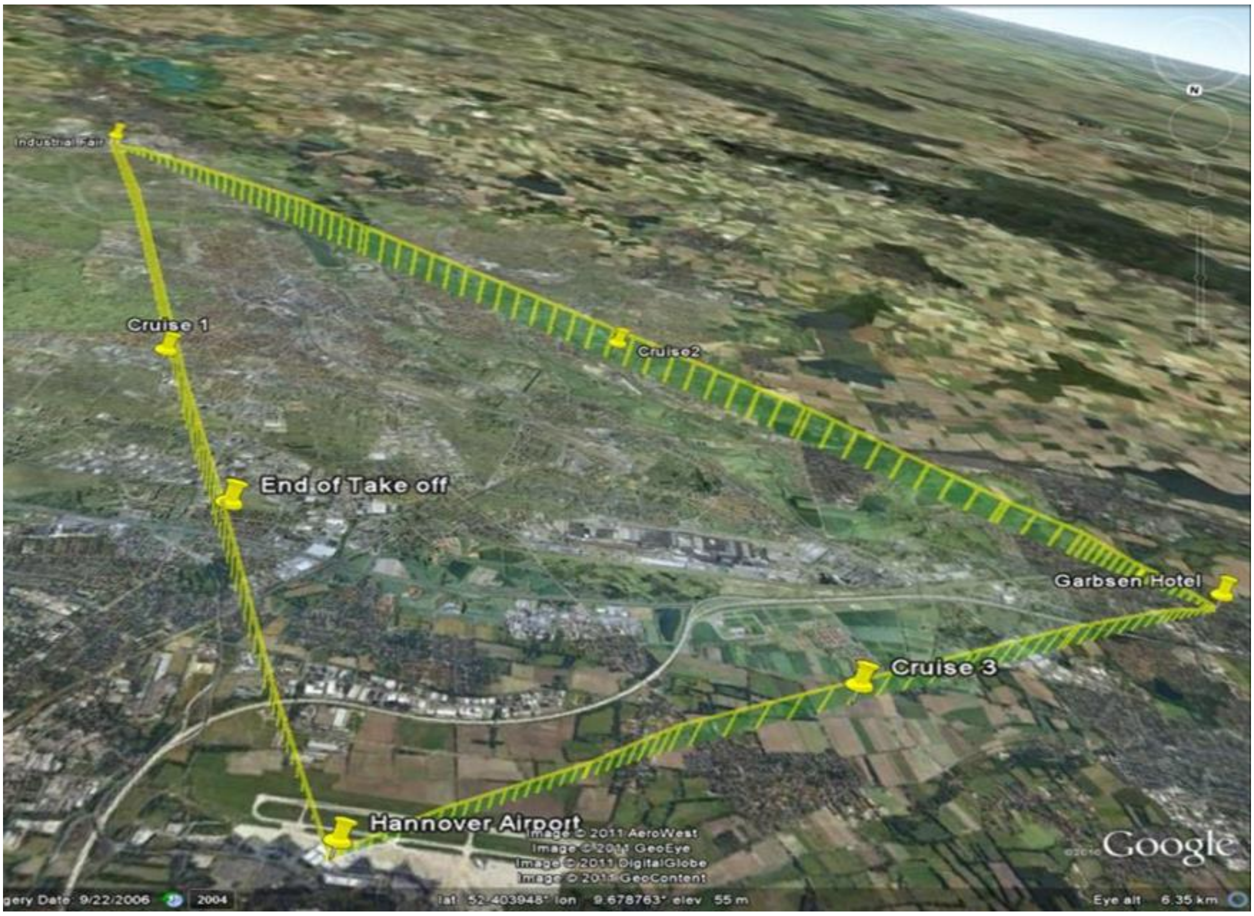

Figure A.1 Default SEL passenger transport mission [6] (NB: in this case North is towards bottom of page)

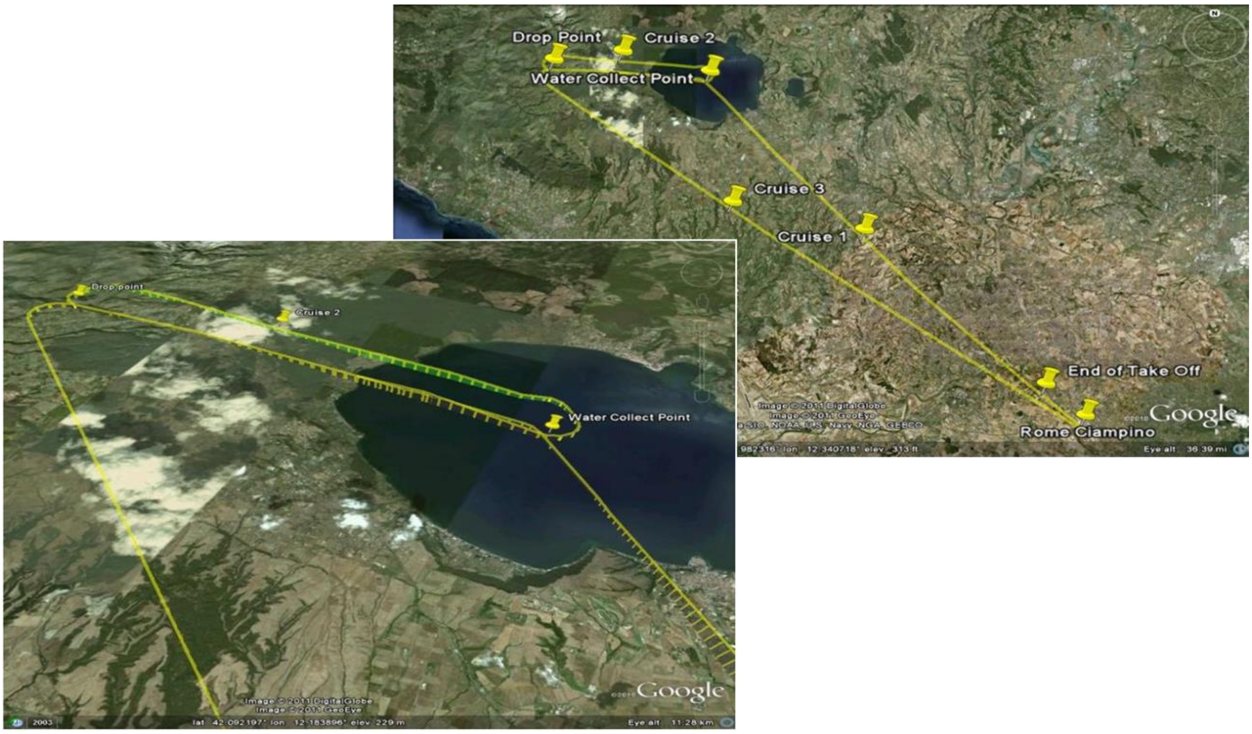

Figure A.2 SEL fire suppression mission [6]

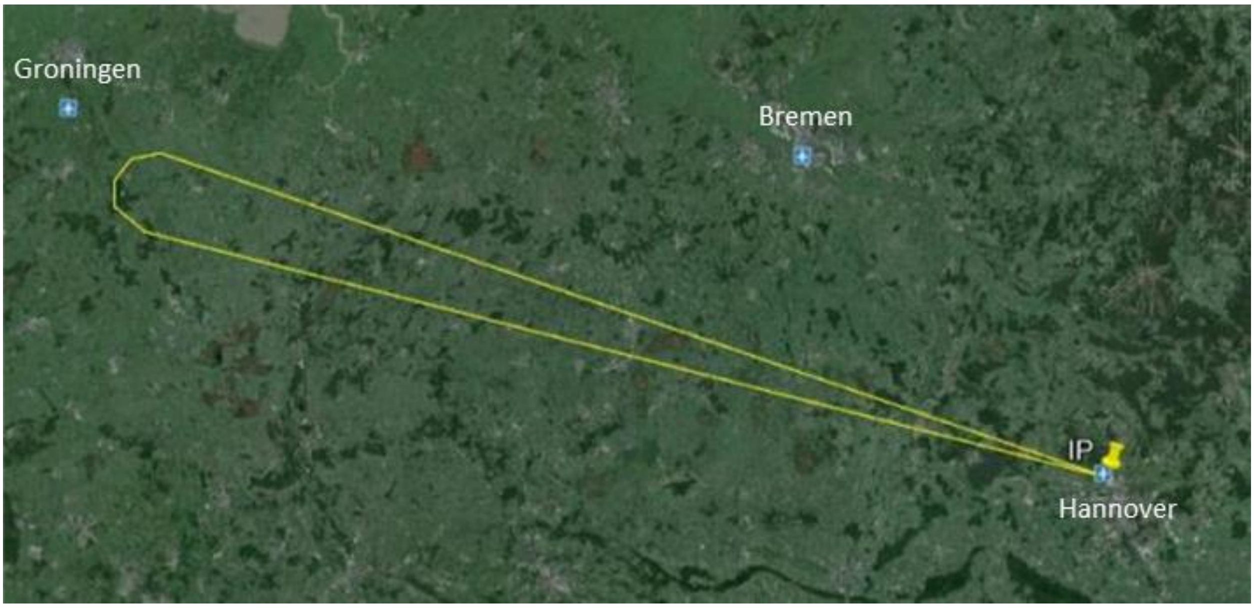

Figure A.3 SEL Long distance, high speed passenger mission [7]

Figure A.4 Default TEH oil/gas mission [6]

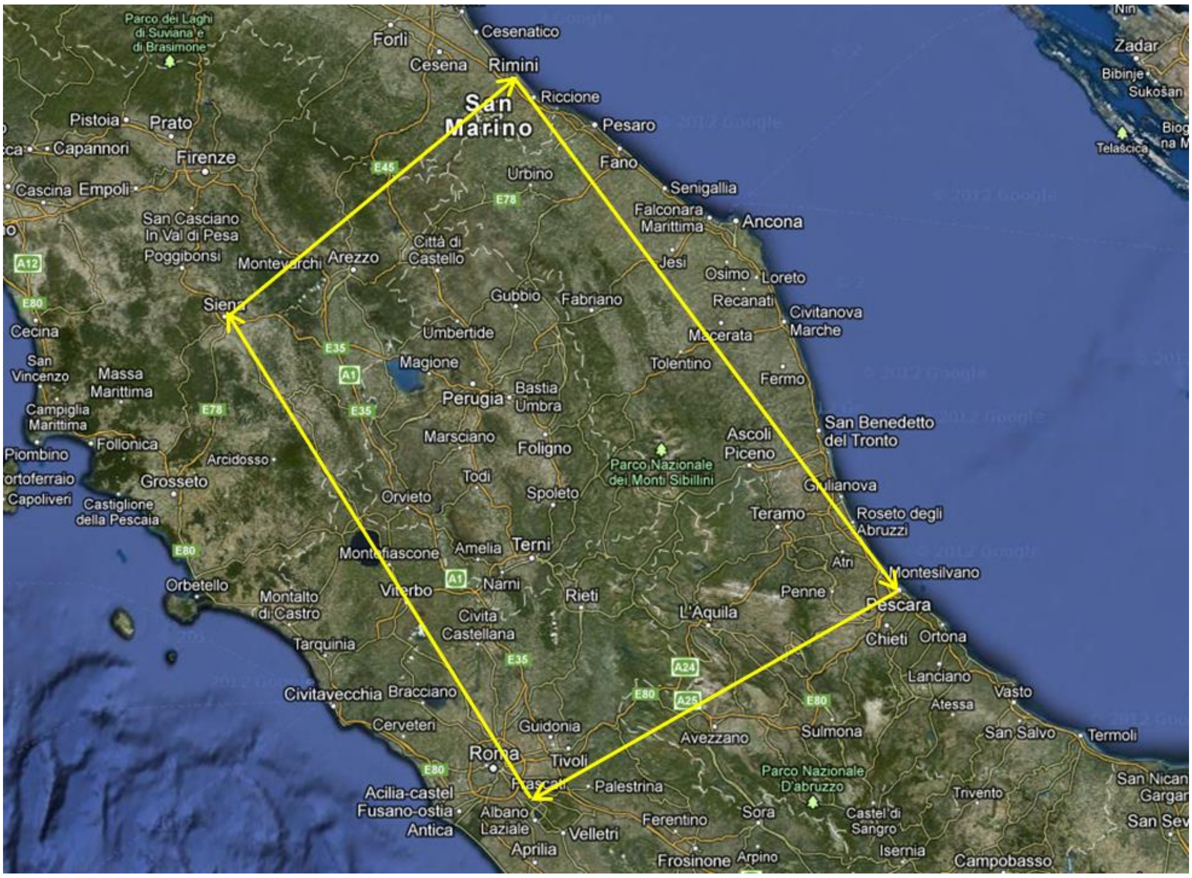

Figure A.5 TEH long range passenger transport mission