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CleanSky Green Rotorcraft New Technologies

Maximizing Noise and Emissions Benefits

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EXECUTIVE SUMMARY

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REPORT NUMBER
NLR-TP-2016-341

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Problem area

Within the CleanSky Joint Technology Initiative the Green Rotorcraft (GRC) Integrated Technology Demonstrator (ITD) and the Sustainable And Green Engine (SAGE) ITD are responsible for developing new (helicopter) technologies. Each GRC subproject performs a trade-off study to maximize the potential benefits of their technology and to choose an appropriate technology for each of the helicopter classes under consideration. The Technology Evaluator (TE) has the distinctive role of assessing the environmental impact of the combined technologies at single flight (mission), at airport and at Air Transport System levels.
Besides the trade-off work already performed by each individual GRC subproject, a need has emerged to perform additional trade-off studies for the complete helicopter with various technologies applied to the generic rotorcraft classes.

Description of work

The trade-off assessments 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 exhaust gas emissions simulation tool (GSP or Turbomeca engine deck) and a noise prediction code (HELENA). PhoeniX can predict the flight performance of a rotorcraft along a prescribed 4D trajectory offering a complete helicopter mission analysis. Three helicopter classes have been examined, being a generic Single Engine Light (SEL) helicopter for passenger transport missions, a generic Twin Engine Light (TEL) helicopter for Emergency Medical Services and Police missions, and a generic Twin Engine Medium (TEM) helicopter for Fire Suppression and Search And Rescue missions. In addition a single engine light helicopter with High Compression Engine (HCE) has been analyzed.

Results and conclusions

The study results show that the adoption of new technologies has a large potential of reducing important metrics like fuel burn, CO2 and NOx gas emissions, and noise footprints between Reference and Conceptual helicopter configurations. The reductions are consistent throughout, with larger benefits being possible for more demanding missions. Potential reductions in fuel burn and CO2 range up to 21% for SEL, 55% for HCE, 7% for TEL and 11% for TEM, whereas potential reductions in NOx range up to 70% for SEL, 66% for HCE, 48% for TEL and 59% for TEM. The adoption of the Low Noise Procedure (LNP) approach, when compared to the reference approach, reduces the 85 SEL (dBA) iso-noise footprint contour area by nearly 90% for SEL and more than 77% for TEL. For TEM the reduction in the 90 SEL (dBA) iso-noise footprint contour area amounts to about 80%.

Applicability

The study results will be used by the individual GRC subprojects to assess the potential of their technologies when applied to a complete rotorcraft.

GENERAL NOTE

This report is based on a presentation held at the 42nd European Rotorcraft Forum, Lille, September 6-8, 2016.

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Summary

The CleanSky Joint Technology Initiative (JTI) is one of the largest European research programmes ever. Within JTI the Green Rotorcraft (GRC) Integrated Technology Demonstrator (ITD), the Sustainable And Green Engine (SAGE) ITD and the Technology Evaluator (TE) are active. The GRC and SAGE ITDs 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). The new technologies encompass systems such as innovative rotor blades, improved airframe designs, integration of High-Compression Engine (HCE) technology, advanced electrical systems, eco-design aspects and improved flight profiles. Their aim is to reduce drag, fuel consumption and exhaust gas emissions, reduce noise, and eliminate the use of noxious hydraulic fluids. Each GRC subproject (GRCi) performs a trade-off study to maximize the potential benefits of their technology and to choose an appropriate technology for each of the helicopter classes under consideration. Besides that trade-off work, a need has emerged to perform additional trade-off studies for the complete rotorcraft with various combinations of technologies, thereby focussing on obtaining the best combination of GRCi technologies in order to achieve the GRC environmental objectives. Because of the inclusion of (new or upgraded) future mission profiles this goes beyond the current TE analysis. As such this study is considered to be a necessary enhancement to the original GRC CleanSky objectives. The assessments have been performed by using a GRC-developed multidisciplinary simulation framework called PhoeniX that comprises computational modules for rotorcraft performance, engine performance and emissions, and noise prediction. Three helicopter classes have been examined, being a Single Engine Light (SEL) configuration, a Twin Engine Light (TEL) configuration and a Twin Engine Medium (TEM) configuration. The results of this study provide detailed insight into the maximum environmental benefits that can be achieved by making use of the GRCi technologies.

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Contents

Abbreviations

ACRONYM	DESCRIPTION
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

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1 Introduction

The worldwide air traffic is expected to increase in quantity sharply in the near future. The present rotorcraft activities in the European Community alone account for an annual average of 1,500,000 flight hours, burning the equivalent of 400000 tons of aviation fuel per year. With the state-of-the-art 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.

To sustain aviation's present environmental impact even after the expected aircraft and rotorcraft fleet growth, the Advisory Council for Aeronautics Research in Europe (ACARE) has established specific environmental goals to be met by the civil aviation industry (including rotorcraft and aircraft) by the year 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

To minimise the future pollution impact of the aeronautics sector the CleanSky Joint Technology Initiative (JTI)[1] was initiated as a public/private partnership between the European Commission and the aeronautical industry, aiming to deliver significant changes to aviation. CleanSky is a consortium that harnesses the best skills and abilities of over eighty-six organizations representing leading European aircraft manufacturers, research and academic institutes. The aim is to construct and operate aircraft, incorporating new and innovative technologies, that meet the targets set by ACARE.

Clean Sky is made-up of several Integrated Technology Demonstrators (ITDs), each one aiming to satisfy the aforementioned ACARE goals, at either vehicle or engine level. With regard to the rotorcraft field, the contributing parties are the Green Rotorcraft (GRC) ITD and the Sustainable and Green Engine (SAGE) ITD. They work alongside the Technology Evaluator (TE), who analyses the environmental impact (noise and emissions), for which the Year 2000 helicopter fleet forms the baseline. Various GRC subprojects (GRCi's), as well as the SAGE ITD, are developing new technologies. GRC's subproject GRC7 'Technology Evaluator for Rotorcraft' prepares rotorcraft fleet data, puts together mathematical computer codes, and defines generic rotorcraft models representing all of the commercial rotorcraft operating in the Year 2000, plus concept designs for the Year 2020+ without and with CleanSky technology. GRC7 also is the interface between the GRC-ITD and the TE.

The object of the current work is to present the novel approach adopted by the GRC-ITD and the TE and its results, which enables the continual environmental impact assessment of the developing CleanSky technologies. 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 demonstrates and validates the technological breakthroughs that are necessary to make major steps towards the overall environmental goals sets by ACARE. Within CleanSky GRC has set the objective to be achieved by the year 2020 as resulting from CleanSky outputs of the GRC and 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, starting from the year 2000-like baseline and consistent with the ACARE targets, the GRC objectives are shown in Fig. 1.

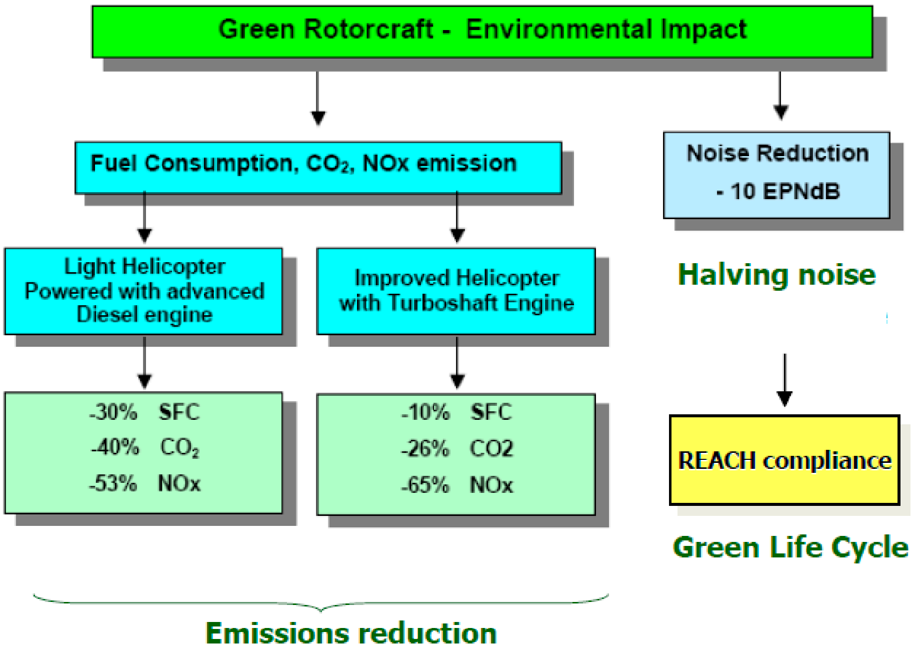

Figure 1: Expected Green Rotorcraft objectives

3 PhoeniX software platform

To enable the assessment of the environmental impact, GRC7 has developed the software tool named PhoeniX (Platform Hosting Operational & ENvironmental Investigations for Rotorcraft), bringing together previously established software programs in a new simulation environment. An architectural overview of the PhoeniX platform is illustrated in Figure 2.

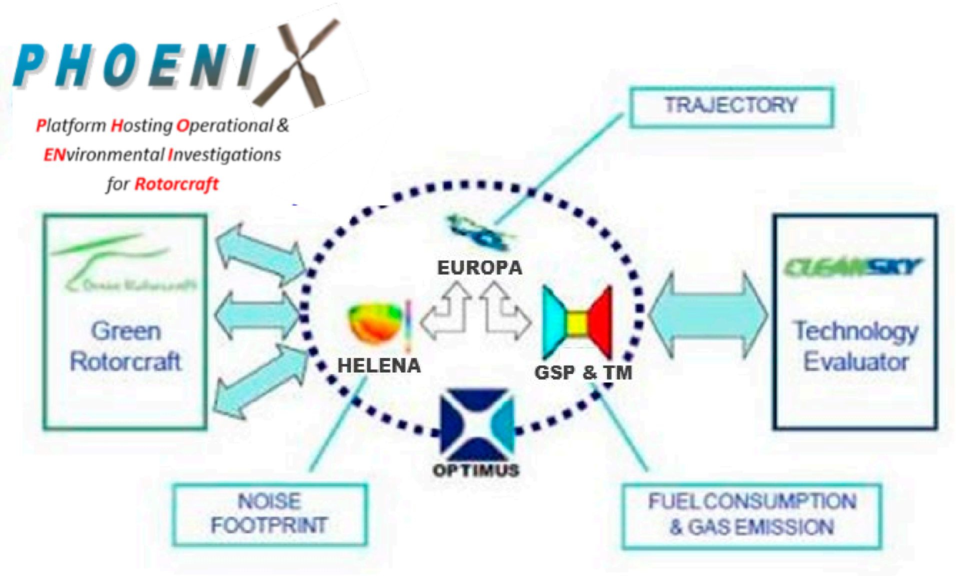

Figure 2: Architectural overview of PhoeniX platform

The platform incorporates the following computational tools:

European Rotorcraft Performance Analysis (EUROPA)

EUROPA is a helicopter flight mechanics code for steady state (trim) and dynamic (manoeuvre) performance simulations. The code was developed and validated in the European RESPECT project[2].

The simulation uses a generic helicopter mission trajectory where properties such as flight conditions, atmospheric conditions and helicopter data are defined by the user. The helicopter flight trajectory output is made up of a number of flight segments, with each segment containing information such as position, altitude, power required, etc. as a function of time. This information is provided to the other tools for fuel burn/gas emissions and noise estimations along the trajectory.

Gas-turbine Simulation Program (GSP)

The Gas-turbine Simulation Program[3] (GSP) is an in-house tool developed by NLR, simulating gas turbine thermodynamic cycles for engine performance (fuel consumption, power output) and exhaust gas emissions. GSP can model any type of gas turbine engine configuration and can handle both steady state and transient calculations, taking into account engine inlet conditions, losses and deterioration.

GSP receives the power required and the atmospheric data from EUROPA and uses the engine characteristics from its own database. At each time step it determines the fuel burn (used for mission mass calculation), generates the exhaust gas emissions and determines the engine power available.

Turbomeca engine deck

Safran's Turbomeca (TM) division is the leading engine manufacturer for helicopters. As an alternative to the GSP code, their engine decks have been introduced for all generic turbine engine helicopter classes. These decks, representing average engines for each helicopter class, calculate steady-state engine performance, fuel burn and exhaust gas emissions.

The implementation of the engine decks is the same as for GSP. In addition however the engine deck for the conceptual helicopter configuration is enhanced by a more accurate representation of the SAGE5 innovative low NOx combustion technology.

Helicopter Environmental Noise Analysis (HELENA)

HELENA is a rotorcraft environmental noise analysis tool used to assess the noise footprints on the ground. The tool was developed and validated within the FRIENDCOPTER[4] research project. The analysis starts from experimental or numerical noise data, contained in noise hemispheres. The hemispheres are determined for main and tail rotor separately for various flight conditions in level flight, climb and descent, thereby taking into account the dynamic behaviour of the rotor blades (e.g. higher harmonic displacements due to the application of Active Gurney Flaps).

The noise propagation models are specifically tailored for rotorcraft noise and take into account distance, wind effects, atmospheric absorption effects, and ground reflection and shielding effects. HELENA receives the trajectory data from EUROPA, and computes the noise levels on the ground 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 process integration simulation framework toolkit and a flexible design environment which can be used to create multidisciplinary simulation frameworks and to evaluate multiple design alternatives. The OPTIMUS implementation of the PhoeniX framework establishes a proper workflow between the aforementioned computational tools. Having its own integrated variety of optimization sequences, OPTIMUS can be used also for trade-off and optimization studies.

PhoeniX methodology

The PhoeniX platform calculates the rotorcraft performance during its specific mission, which is defined using WGS84 coordinates. Realistic missions can be composed using individual flight segments such as hover, take off, cruise, loiter, descent, landing, idle and payload loading/unloading. A typical assessment of rotorcraft fuel consumption, exhaust gas emission and noise during a single mission and for a given set of input data involves the following steps:

- The EUROPA code takes the user defined helicopter data, mission profile, and flight and atmosphere conditions as input. It then returns the helicopter position, attitude, tip path plane angles, power required and atmospheric conditions along the flight path as a function of time.
- The GSP code and Turbomeca engine deck are coupled inside EUROPA. For each time step the engine code receives the atmospheric conditions and power required, and calculates the fuel burn and the exhaust gas emissions. After the successful convergence of the mission fuel, OPTIMUS post processes the results to produce the total amount of fuel and exhaust gases for the entire trajectory.
- After the convergence OPTIMUS also passes the flight trajectory data to HELENA in the appropriate format. HELENA then determines the noise footprints for the given flight conditions and trajectory. OPTIMUS also post processes those results to produce the maximum noise levels.

4 Helicopter configurations and classes

GRC have defined three helicopter configurations:

- the Year 2000 Baseline (B), which corresponds to existing technology and concepts which were built until the year 2000
- the Year 2020 Reference (R), which corresponds to projected technologies up until the year 2020 without newly-developed CleanSky benefits
- the Year 2020 Conceptual (C), which corresponds to projected technologies up until the year 2020 with specific CleanSky technological developments like e.g. innovative rotor blades or drag reductions; the applied technologies are detailed in chapter 5

For each configuration four classes of baseline generic (turbine-powered) helicopters have been defined, based on All-Up Mass (AUM), and on type and number of engines:

- Single Engine Light (SEL) with AUM ≤ 4 metric tons and one gas turbine engine
- Twin Engine Light (TEL) with AUM ≤ 4 metric tons and two gas turbine engines
- Twin Engine Medium (TEM) with 4 ≤ AUM ≤ 8 metric tons and two gas turbine engines
- Twin Engine Heavy (TEH) with AUM > 8 metric tons and two gas turbine engines

In addition the following class has been defined for the Year 2020 Conceptual configuration only:

- High Compression Engine (HCE) with AUM ≤ 4 metric tons and one high compression piston engine

5 CleanSky technologies

New technologies are being developed by various GRCi's and by the SAGE ITD. These technological 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. The objectives and new technologies for each GRCi and for SAGE are summarized in the following sections. Details about which technology has been included on what helicopter class are provided in Table A.1.

5.1 GRC1 Innovative rotor blades

The objective of GRC1 is the development of active and passive technologies to provide the greatest possible reductions in rotor noise and fuel consumption, and to achieve significant performance benefits. Adopted technologies are:

- Passive Optimized Blades (POB), having optimized blade's geometry and aerodynamic profile section
- Active Gurney Flaps (AGF), delaying the onset of retreating blade stall, reducing collective pitch at high speeds, and facilitating a reduction in main rotor speed and thus in thickness noise
- Active Blade Twist (ABT), facilitating performance benefits in helicopter cruise flight or acoustic benefits on approach to landing (ABT would be used for only one benefit at a given time)

5.2 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

5.3 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
- Electromagnetic actuators for helicopter flight control
- Efficient power generation and control for piezoelectric actuation, esp. active blades
- Electrically driven tail rotor

5.4 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
- Integration of the engine minimising the potential adverse effects of weight penalty, vibration and cooling system

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

5.5 GRC5 Environmentally-friendly flight path

The objectives of GRC5 are:

- Reducing noise footprint and noise impact
- Minimising 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

5.6 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

5.7 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 adopted technologies will deliver:

- Improved specific fuel consumption
- Reduced exhaust gas emissions
- Reduced noise

6 Trade-off studies

Each GRCi has performed trade-off work for individual technologies. The TE has analysed the impact of all technologies together, and for default missions which are representative for the Year 2000 timeframe and that do not change when going from Baseline to Reference to Conceptual helicopter. Those missions are representative for the various helicopter classes and have been defined by the TE in consultation with helicopter manufacturers and operators. Besides the aforementioned GRCi trade-off work and the TE analysis, a need has emerged to perform additional trade-off studies for the complete rotorcraft with various technologies installed. And also to include the definition of (new or upgraded) future mission profiles that will be made possible thanks to those technologies, thereby taking full advantage of the potential benefits of those new 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 (complete) models in the PhoeniX software platform.

This more detailed study, assessing the impact of individual technologies, has been performed by GRC7. The combined implementation of individual technologies may lead to mutual interactions. E.g. a reduction in fuselage drag area has an impact on power required (and thus on the installed engine) and on fuel consumption. This then will have an effect on the All-Up Mass (AUM) and rotor dimensions. So, ideally one would start off from the Year 2020 Reference helicopter and add the individual technologies one at a time. For each added technology, the complete helicopter would need to be re-sized. Moreover, also a complete set of noise hemispheres would need to be derived. As such an approach would require far too much effort, 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 re-sizing the helicopter.

Such a technology impact assessment has been carried out for all generic helicopter classes. The analysis results for the SEL and TEH configurations have been reported before[6]. As the SEL configuration has been updated since, a new assessment has been carried out. Those updated results are reported here, together with the (new) assessment results for TEL and TEM. These three classes represent resp. 57%, 15% and 18% of the Year 2000 worldwide helicopter fleet that totalled more than 16600 individual helicopters (Fig. 3).

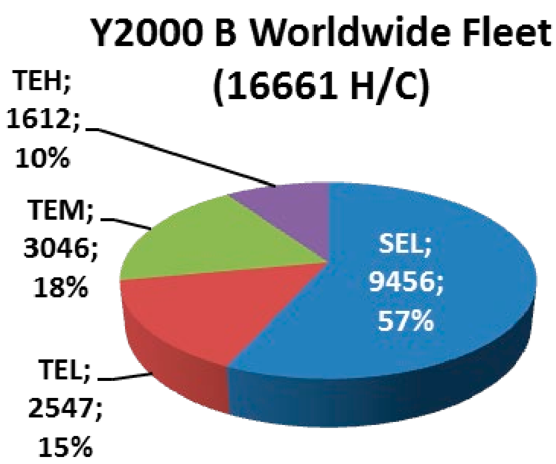

Figure 3: Year 2000 worldwide helicopter fleet

7 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). Technology details are provided in Table A.1. The following cases have been analysed:

1. SEL-R
2. SEL-R with POB at 100% rotor rpm
3. SEL-R with reduced drag for rotor head, fuselage and skids; this includes 14.3 kg additional weight
4. SEL-R with 21 kg weight reduction
5. SEL-R with SEL-C engine model and dynamic air intake
6. SEL-C
7. HCE-C (SEL-C with HCE engine); only for more demanding mission '2'

7.1 Default passenger mission

The initial analysis has been carried out for the default SEL passenger transport mission (Fig.4). Details can be found in Table A.2.

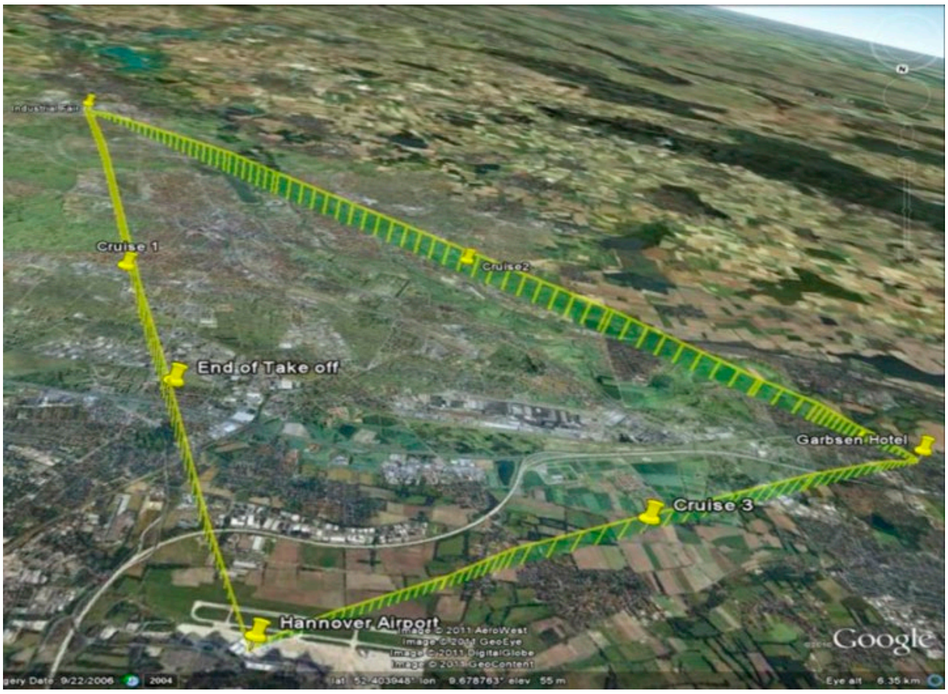

Figure 4: Default SEL passenger transport mission[7]

The helicopter takes off from Hannover Airport (Germany) to pick up four passengers from a secondary location. It subsequently transfers them to the local Garbsen Hotel and then transits back to Hannover Airport where it originated from. The selected route is not restrained by noise abatement procedures.
The analysis results are shown in Table 1.

Table 1: SEL trade-off results for passenger mission

Case	Δ Fuel (%)	Δ CO2 (%)	Δ NOx (%)
1	0	0	0
2	-0.6	-0.6	-1.4
3	-3.1	-3.1	-7.3
4	-0.3	-0.3	-0.6
5	-9.8	-9.8	-41.1
6	-15.9	-15.8	-49.7

7.2 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
- The benefit of the new engines is an overall benefit, independent of the mission profile

With the foregoing in mind two new, more demanding, mission profiles have been defined, that can show a larger benefit for 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 are further detailed in the next section.

7.3 More demanding missions

The fire suppression mission (Fig. 5) is based on the default fire suppression mission defined for the 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. After the water bucket has been filled, the helicopter flies to the location of the fire and drops the water on the fire. Various sorties are flown between the water collection point and the fire zone. Finally, the helicopter will fly back to and land at the original helipad.

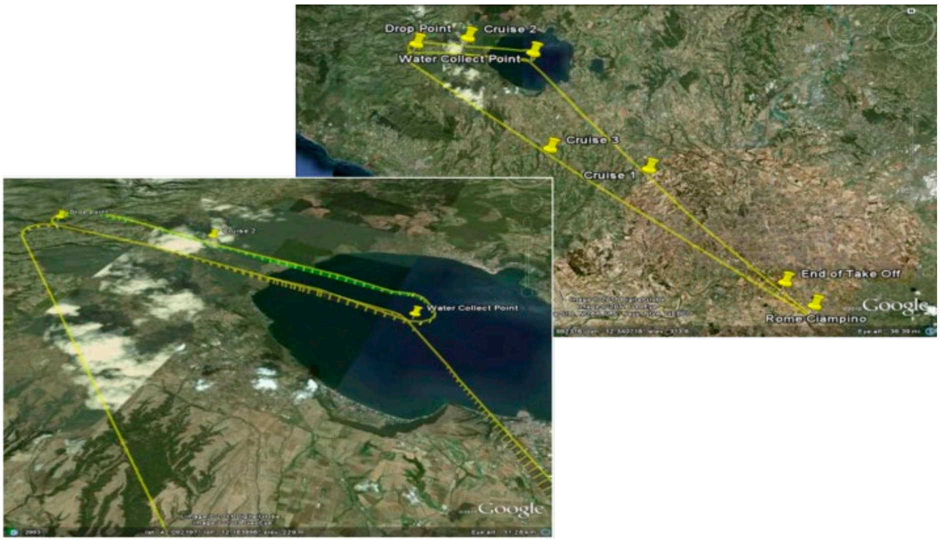

Figure 5: SEL fire suppression mission[7]

The long distance, high speed passenger transport mission (Fig. 6) is based on the default Hot and High mission defined for the HCE helicopter.

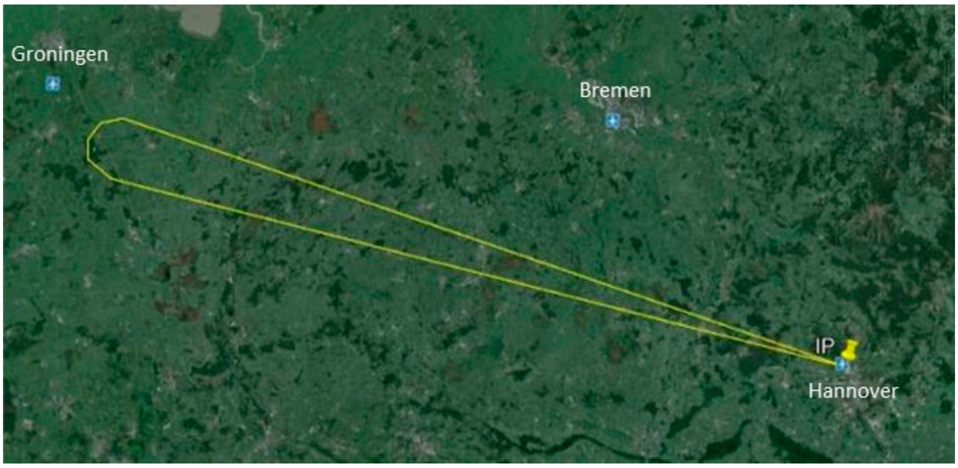

Figure 6: SEL long distance, high speed passenger mission[8]

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. More details for both missions can be found in Table A.2.

The analysis results for the fire suppression mission are shown in Table 2, those for the far/fast mission in Table 3 (the latter mission has also been analysed for the HCE helicopter class, case 7).

Comparing Tables 1 and 2 shows a small increase in fuel and CO2 benefits for individual technologies, but not for the combined technologies. The benefit on NOx production for Case 5 has increased by more than 12 percent points and for the combined technologies has increased by about 10 percent points.

Table 2: SEL trade-off results for fire suppression mission

Case	Δ Fuel (%)	Δ CO2 (%)	Δ NOx (%)
1	0	0	0
2	-1.7	-1.7	-3.3
3	-3.4	-3.4	-6.7
4	-0.5	-0.5	-0.9
5	-10.8	-10.8	-53.8
6	-15.7	-15.7	-59.4

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

Case	Δ Fuel (%)	Δ CO2 (%)	Δ NOx (%)
1	0	0	0
2	-1.6	-1.6	-2.7
3	-9.9	-9.9	-16.6
4	-0.1	-0.1	-0.1
5	-9.9	-9.9	-54.2
6	-21.1	-21.1	-70.0
7	-55.2	-55.3	-66.4

Comparing Tables 1 and 3 shows a clear increase in fuel and CO2 benefits for Case 3. The benefits on NOx production for Cases 3 and 5 have increased by 9-13 percent points. For the combined technologies the benefits for all three parameters have increased, for NOx even by about 20 percent points.

The incorporation of the High Compression Engine has a clear benefit on fuel burn and CO2 (reduction of about 55%) and on NOx (reduction of about 66%).

7.4 Noise trade-off study

GRC5 has defined 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 100kts (see Fig. 7).

The reference approach is flown at about 62kts 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.

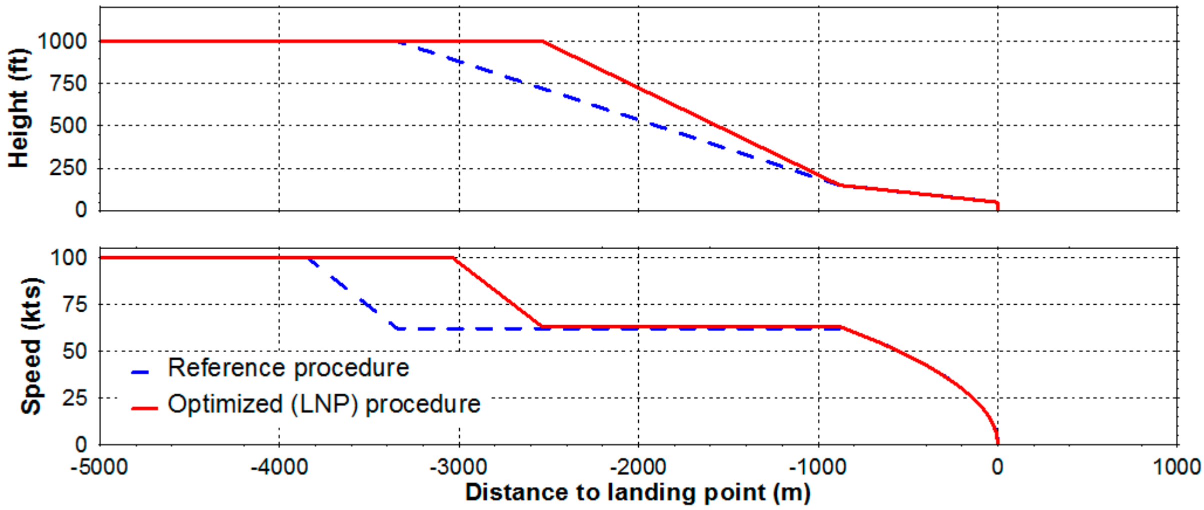

Figure 7: Height-speed profiles for SEL reference and LNP approach

As elucidated in chapter 6 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, in which noise footprint plots have been derived for the approach plus 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 at coordinates Xac=0, Yac=0.

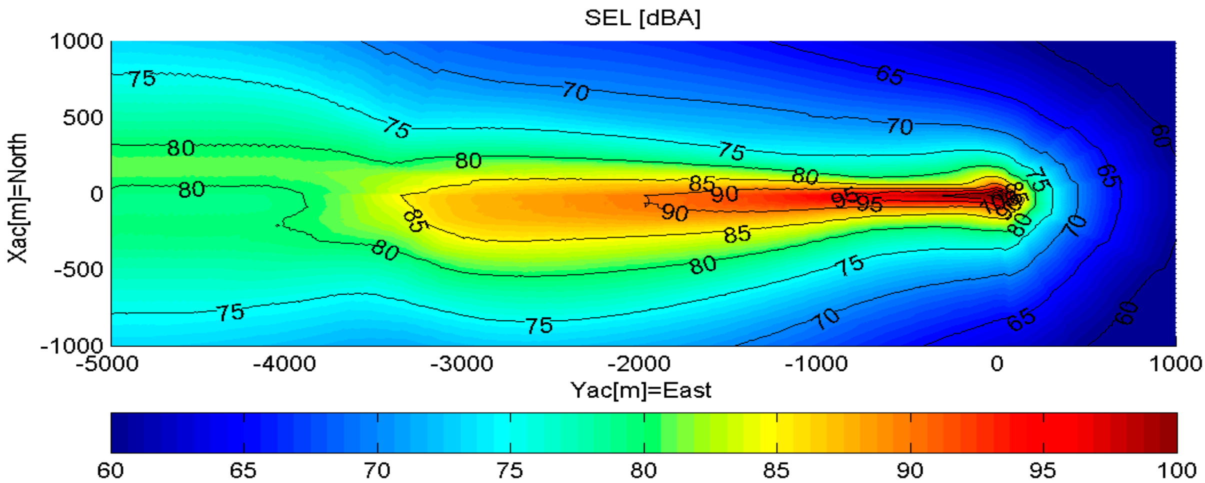

Figure 8: Noise footprint plot for SEL-R, reference approach (at 100% rotor rpm)

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

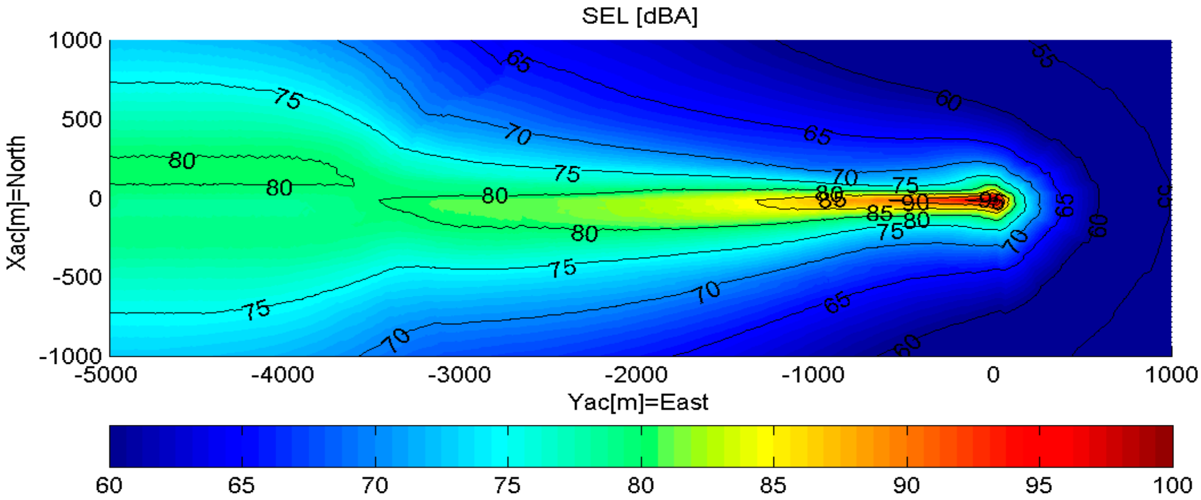

Figure 9: Noise footprint plot for SEL-C, reference approach (at 95% rotor rpm)

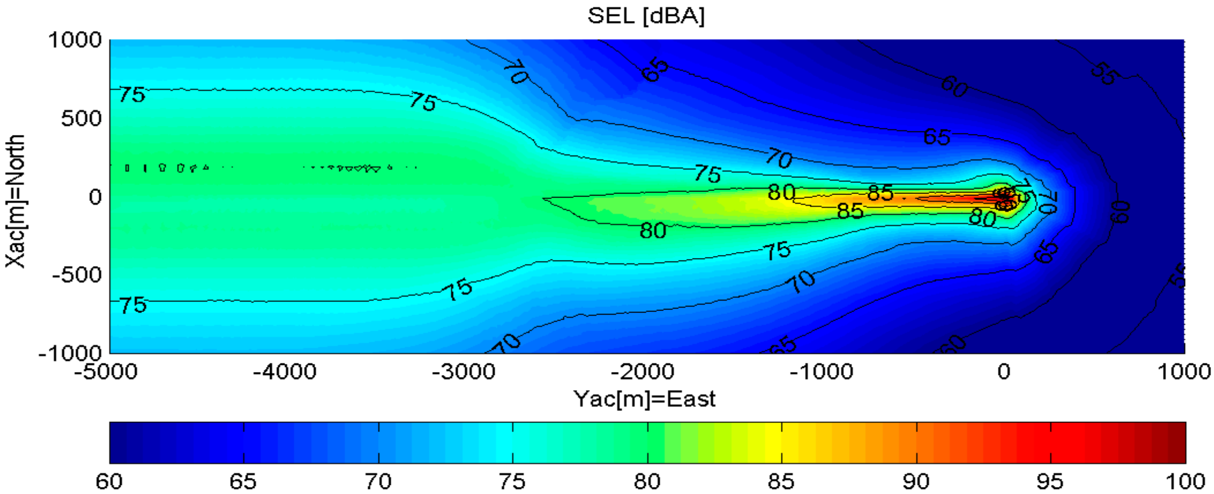

Figure 10: Noise footprint plot for SEL-C, LNP approach (at 95% rotor rpm)

For SEL-C with LNP approach there is a (slightly) larger 75 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 2500m 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.

Finally, Table 4 provides the 85 SEL (dBA) iso-noise contour area reductions for the three combinations, showing that a reduction of nearly 90% is achievable.

Table 4: SEL noise analysis for approach and landing phase, 85 SEL (dBA) iso-noise contour areas

Combination	Δ Area (%)
SEL-R, Reference Approach	0
SEL-C, Reference Approach	-88.5
SEL-C, LNP Approach	-89.7

8 Twin Engine Light (TEL) helicopter

This chapter quantifies the impact of the individual technologies that have been implemented on the Year 2020 Conceptual Twin Engine Light helicopter (TEL-C) Technology details are provided in Table A.1. The following cases have been analysed:

1. TEL-R
2. TEL-R with POB at 100% rotor rpm
3. TEL-R with reduced drag for rotor head, fuselage and skids
4. TEL-R with 7.1 kg weight reduction
5. TEL-R with TEL-C engine model and dynamic air intake
6. TEL-C

8.1 Default EMS and police missions

The initial analysis has been carried out for the default TEL Emergency Medical Services (EMS) mission and the default TEL police mission. Details for both missions can be found in Table A.2.

For the EMS mission (Fig. 11) the helicopter travels directly from Ciampino airport (Rome) to a designated rescue zone of a hypothetical traffic accident that has occurred on the A90 Motorway (near Vatican City Rome). The helicopter collects the injured civilians and transports them to the nearest available hospital (Policlinico Gemelli Hospital) and subsequently transits back to its originating helipad at Ciampino airport (Rome). The selected route is not restrained by noise abatement procedures.

Figure 11: TEL EMS mission[7]

For the police mission (Fig. 12) the helicopter takes off from Myttinge Heliport (Stockholm), to conduct high altitude surveillance in two different areas. The mission is mainly conducted over Stockholm. Once completed the helicopter transits back to Myttinge Heliport. The selected route is not restrained by noise abatement procedures.

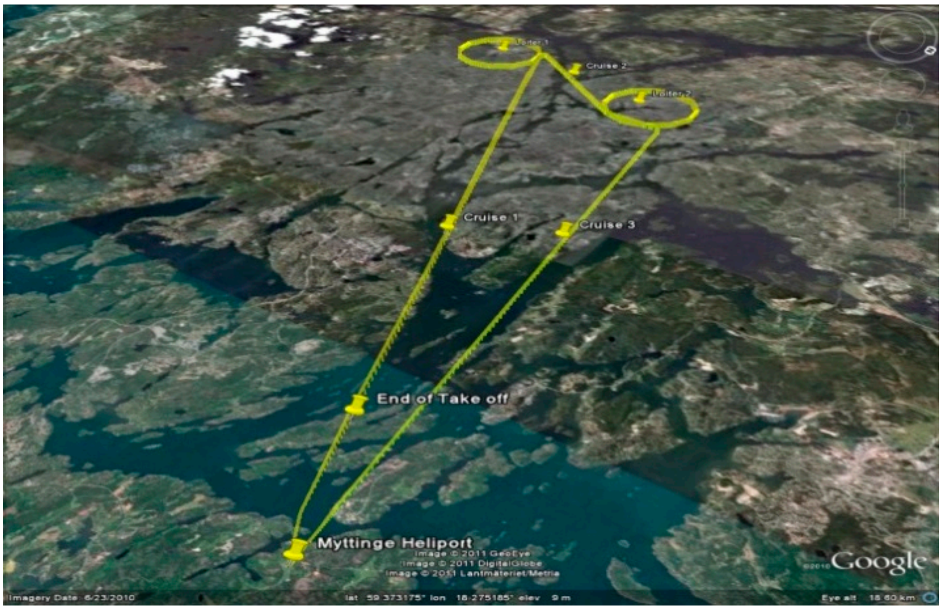

Figure 12: TEL police mission[7]

The analysis results for the EMS mission are shown in Table 5, those for the police mission in Table 6.

Table 5: TEL trade-off results for EMS mission

Case	Δ Fuel (%)	Δ CO2 (%)	Δ NOx (%)
1	0	0	0
2	-0.5	-0.5	-1.3
3	-0.7	-0.7	-1.6
4	-0.1	-0.1	-0.2
5	-3.0	-2.9	-30.6
6	-5.4	-5.4	-34.7

Table 6: TEL trade-off results for police mission

Case	Δ Fuel (%)	Δ CO2 (%)	Δ NOx (%)
1	0	0	0
2	-0.7	-0.7	-1.7
3	-0.6	-0.6	-1.6
4	-0.1	-0.1	-0.2
5	-3.1	-3.1	-17.8
6	-4.8	-4.8	-22.0

8.2 Discussion of results

The default EMS mission is rather short and flown at moderate mass, with the police mission being somewhat more demanding. Both missions however do not use the full potential of the TEL helicopter. The TEL helicopter uses similar technologies as the SEL helicopter and one can discern similar 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
- The benefit of the new engines is an overall benefit, independent of the mission profile

With the foregoing in mind two new, more demanding, mission profiles have been defined for the TEL helicopter that can show a larger benefit for the adopted technologies. These two missions are based on the more demanding SEL missions. A considerable part of the fire suppression mission profile is flown in hover or low speed, meriting the use of Passive Optimized Blades. The high cruising speed in the long distance passenger transport mission 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 are further detailed in the next section.

8.3 More demanding missions

The missions are derived from the two more demanding SEL missions, with the following differences. For the fire suppression mission the capacity of the water tank has been increased. For the long distance passenger transport mission the payload and cruising speed have been increased, and a single circular observation pattern is included (to increase the mission duration). Details for both missions can be found in Table A.2.

The analysis results for the fire suppression mission are shown in Table 7, those for the far/fast mission in Table 8.

Comparing Tables 5/6 against Table 7 shows a small increase in fuel and CO2 benefits for most technologies. The benefit on NOx production for Case 5 has increased by up to 26 percent points and for the combined technologies has increased by up to 20 percent points.

Table 7: TEL trade-off results for fire suppression mission

Case	Δ Fuel (%)	Δ CO2 (%)	Δ NOx (%)
1	0	0	0
2	-1.5	-1.5	-3.2
3	-0.8	-0.8	-1.8
4	-0.1	-0.1	-0.3
5	-3.0	-3.0	-43.6
6	-5.6	-5.6	-42.6

Table 8: TEL trade-off results for far/fast mission

Case	Δ Fuel (%)	Δ CO2 (%)	Δ NOx (%)
1	0	0	0
2	-1.1	-1.1	-2.1
3	-2.6	-2.6	-5.2
4	0	0	-0.1
5	-3.2	-3.2	-42.9
6	-7.2	-7.2	-47.5

Comparing Tables 5/6 and Table 8 shows clear increases in fuel and CO2 benefits for Cases 2 and 3. The benefits on NOx production for Case 5 have increased by up to 25 percent points. For the combined technologies the benefits for all three parameters have increased, for NOx by up to 25 percent points.

8.4 Noise trade-off study

Similar to SEL, GRC5 has defined noise-optimized LNP approach procedures for TEL, with TEL-B and TEL-R using the reference (baseline) approach, and TEL-C the LNP approach. Both approaches start in level flight at a height of 1000ft and a speed of 100kts (see Fig. 13).

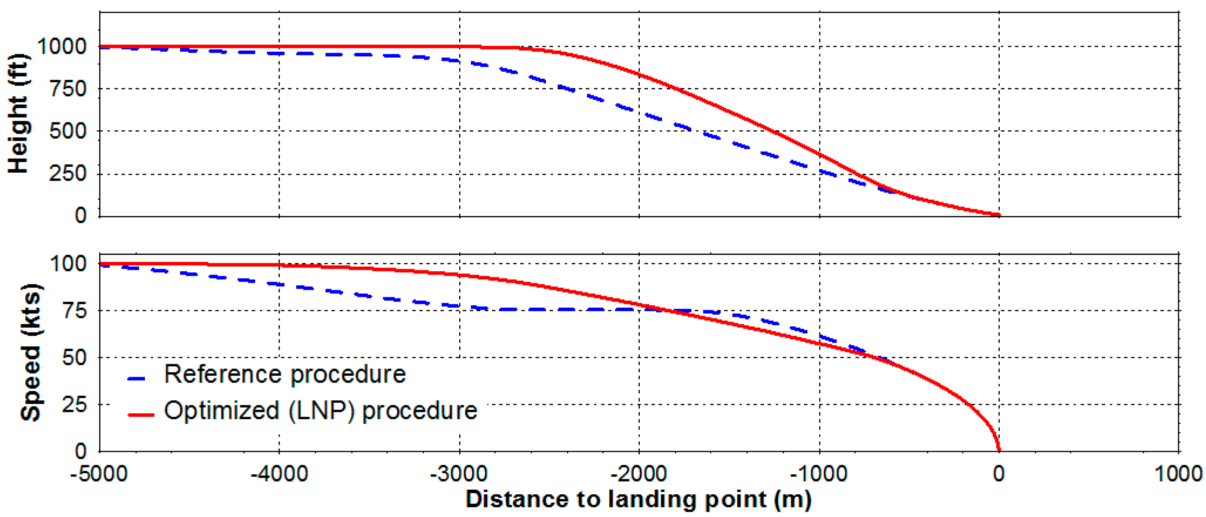

Figure 13: Height-speed profiles for TEL reference and LNP approach

The reference approach is initially flown at about 75kts with a 6 degree descent angle from 1000ft down to about 500 ft, where a deceleration is started. The LNP approach adopts a decelerating flight path at 9 degrees descent angle from 1000ft. From the flare point down to the landing point the forward and vertical speed components are gradually reduced.

Noise footprint plots have been derived for the approach plus landing for:

- TEL-R with reference approach (Fig. 14)
- TEL-C with reference approach (Fig. 15)
- TEL-C with LNP approach (Fig. 16)

In all figures the helicopter approaches from the left and lands at coordinates Xac=0, Yac=0.

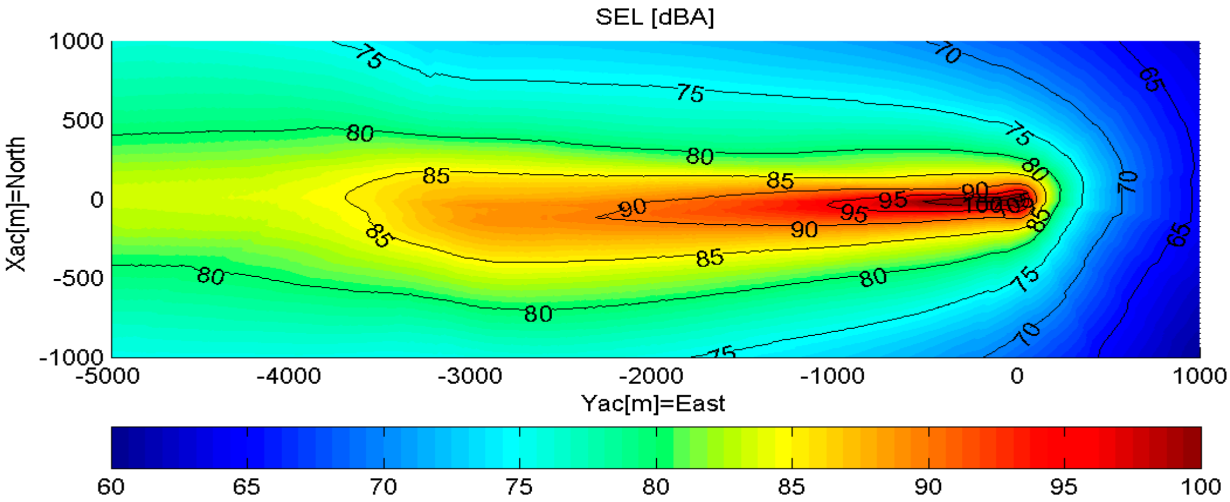

Figure 14: Noise footprint plot for TEL-R, reference approach (at 100% rotor rpm)

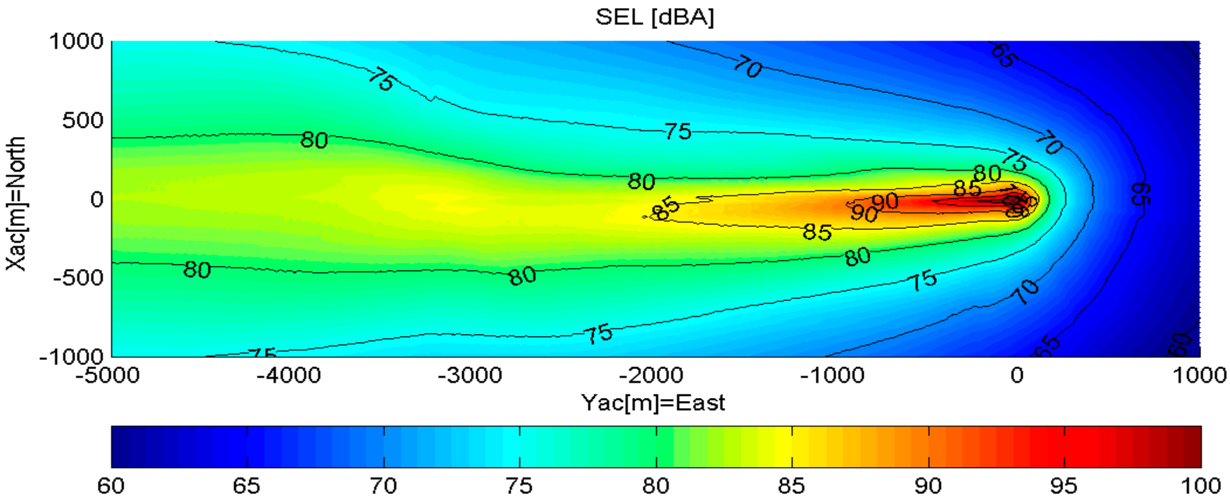

Figure 15: Noise footprint plot for TEL-C, reference approach (at 95% rotor rpm)

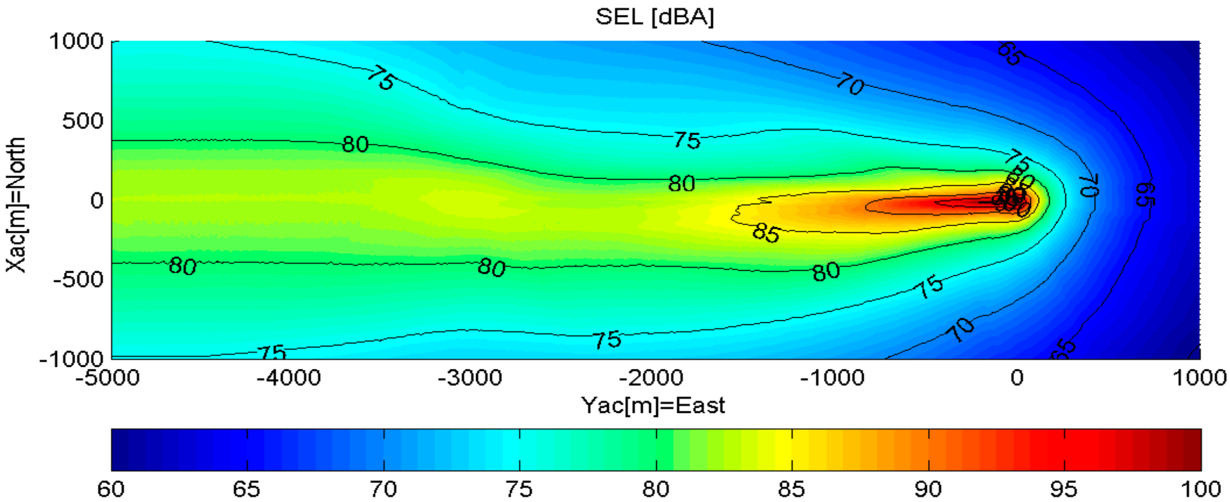

Figure 16: Noise footprint plot for TEL-C, LNP approach (at 95% rotor rpm)

Going from Fig. 14 to Fig. 15 there is a considerable reduction in noise levels, which is mainly attributable to the use of POB on TEL-C (which also facilitates a reduction in rotor rpm). Going from Fig. 15 to Fig. 16 the differences stem from the adoption of a steeper approach flight path angle during the LNP approach.

Finally, Table 9 provides the 85 SEL (dBA) iso-noise contour area reductions for the three combinations, showing that a reduction of more than 77% is achievable.

Table 9: TEL noise analysis for approach and landing phase, 85 SEL (dBA) iso-noise contour areas

Combination	Δ Area (%)
TEL-R, Reference Approach	0
TEL-C, Reference Approach	-73.7
TEL-C, LNP Approach	-77.4

9 Twin Engine Medium (TEM) helicopter

This chapter quantifies the impact of the individual technologies that have been implemented on the Year 2020 Conceptual Twin Engine Medium helicopter (TEM-C) Technology details are provided in Table A.1. The following cases have been analysed:

1. TEM-R
2. TEM-R with POB at 100% rotor rpm
3. TEM-R with AGF at 100% rotor rpm
4. TEM-R with reduced drag for rotor head and skids
5. TEM-R with 21.9 kg weight increase
6. TEM-R with TEM-C engine model and dynamic air intake
7. TEM-C

AGF and Electric Tail rotor Drive (ETD) on the one hand increase the helicopter's weight, on the other hand they also have clear beneficial effects (introducing ETD will bring removal of hydraulics, reduced maintenance and improved safety). Furthermore the AGF turns out not to be so effective on TEM in its current configuration (low disk loading, high solidity, high main rotor tip speed). Therefore some additional cases have been introduced:

3B. As Case 3, but with AGF at 95% rpm for the entire 'more demanding' mission; this increases the rotor thrust loading and thus the AGF benefits; it is to be remarked that the practical engineering considerations of this idea have not been elaborated yet

5B. As Case 5, but without AGF and ETD; showing the effect of a weight reduction

7B. As Case 7, but without AGF and ETD; showing the effect of a weight reduction

9.1 Default fire suppression and SAR missions

The initial analysis has been carried out for the default TEM fire suppression mission (the description of this mission already has been provided in section 7.3) and the default TEM Search And Rescue (SAR) mission. Details for both missions can be found in Table A.2.

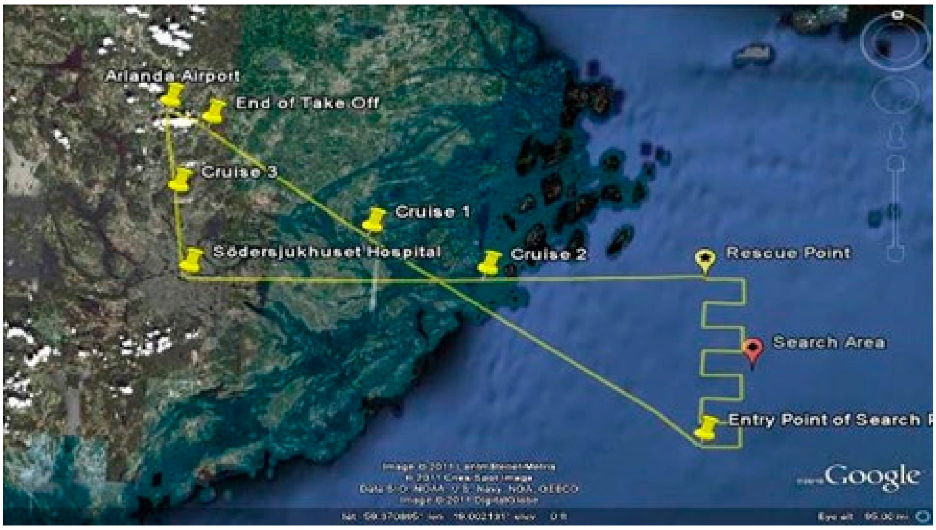

Figure 17: TEM Search And Rescue mission[7]

For the SAR mission (Fig. 17) the helicopter travels directly from Arlanda Airport in Stockholm (Sweden) towards the designated search and rescue area. It subsequently performs a detailed scan within the designated search zone perimeter by using a parallel track search pattern. Upon sight, the helicopter will transit to the incident point and collect the civilian(s) in distress transporting them to the hospital. The helicopter will subsequently head back directly to the original helipad. The selected route is not restrained by noise abatement procedures.

The analysis results for the fire suppression mission are shown in Table 10, those for the SAR mission in Table 11.

Table 10: TEM trade-off results for fire suppression mission

Case	Δ Fuel (%)	Δ CO2 (%)	Δ NOx (%)
1	0	0	0
2	-1.6	-1.6	-3.4
3	+0.3	+0.3	+0.7
4	-1.0	-1.0	-1.8
5	+0.2	+0.2	+0.4
5B	-0.5	-0.5	-1.0
6	-6.2	-6.2	-47.4
7	-8.5	-8.5	-43.8
7B	-9.1	-9.1	-43.9

Table 11: TEM trade-off results for SAR mission

Case	Δ Fuel (%)	Δ CO2 (%)	Δ NOx (%)
1	0	0	0
2	-1.0	-1.0	-2.0
3	+0.3	+0.3	+0.5
4	-1.3	-1.3	-2.7
5	+0.1	+0.1	+0.3
5B	-0.3	-0.3	-0.6
6	-6.3	-6.3	-29.6
7	-8.6	-8.6	-35.3
7B	-8.9	-8.9	-36.3

9.2 Discussion of results

The duration of both TEM default missions is about 2½ hrs, which is the maximum achievable. The helicopter weight and fuel load are close to their maximum. However, those missions do not use the full potential of the TEM helicopter from the perspective of flight conditions. 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; it is to be noted that the fire suppression mission already has a large hover content
- 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 or increase) has a small impact

- The benefit of the new engines is an overall benefit, independent of the mission profile

With the foregoing in mind a new, more demanding, mission profile has been defined for the TEM helicopter, aimed at maximizing the benefit of the AGF and of the reduced drag levels. For this, 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.

9.3 More demanding missions

The long range passenger transport mission (Figure 18) starts from Rome Airport and then flies to Perugia, Rimini, Ancona and back to Rome, crossing the Apennine Mountains twice. Details can be found in Table A.2.

Figure 18: TEM long range passenger transport mission

The analysis results for the long range passenger transport mission are shown in Table 12.

Comparing Tables 10/11 against Table 12 shows an increase in fuel and CO_2 benefits for Case 4. The benefits on NO_x production for Case 6 have increased by up to 21 percent points. For the combined technologies the benefits for all three parameters have increased, for NO_x even by up to 22 percent points. As expected the effect of AGF remains small for all missions. Only case 3B (reduced rotor rpm throughout the complete mission) does show benefits from AGF for all parameters.

Table 12: TEM trade-off results for long range mission

Case	Δ Fuel (%)	Δ CO2 (%)	Δ NOx (%)
1	0	0	0
2	-1.0	-1.0	-2.1
3	+0.2	+0.2	+0.4
3B	-2.8	-2.8	-5.9
4	-2.7	-2.7	-5.4
5	+0.1	+0.1	+0.3
5B	-0.4	-0.4	-0.8
6	-6.6	-6.6	-50.3
7	-10.1	-10.1	-56.9
7B	-10.7	-10.7	-58.5

9.4 Noise trade-off study

Similar to SEL and TEL, GRC5 has defined noise-optimized LNP approach procedures for TEM, with TEM-B and TEM-R using the reference (baseline) approach, and TEM-C the LNP approach. Both approaches start in level flight at a height of 1700ft and a speed of about 90kts (see Fig. 19).

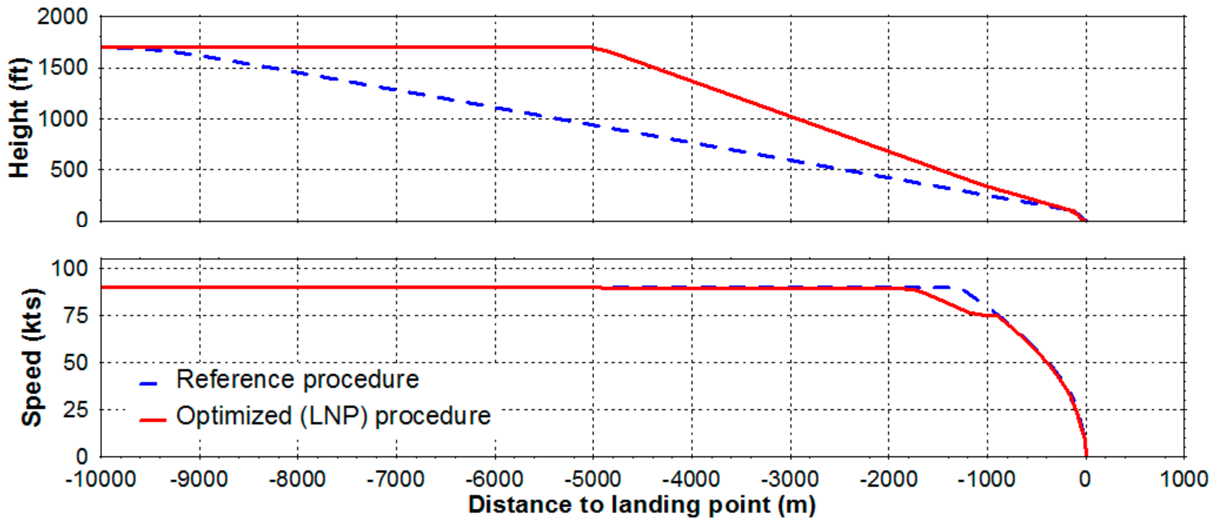

Figure 19: Height-speed profiles for TEM reference and LNP approach

The reference approach is flown at about 90kts with a 3 degree descent angle from 1700ft down to the flare height at 150 ft. Speed reduction is started at a height of about 300ft. The LNP approach uses a 6 degrees descent angle from 1700ft down to 150ft, with a speed reduction being started at about 700 ft. From the flare point down to the landing point the forward and vertical speed components are gradually reduced.

Noise footprint plots have been derived for the approach plus landing for:

- TEM-R with reference approach (Fig. 20)
- TEM-C with reference approach (Fig. 21)
- TEM-C with LNP approach (Fig. 22)

In all figures the helicopter approaches from the left and lands at coordinates Xac=0, Yac=0.

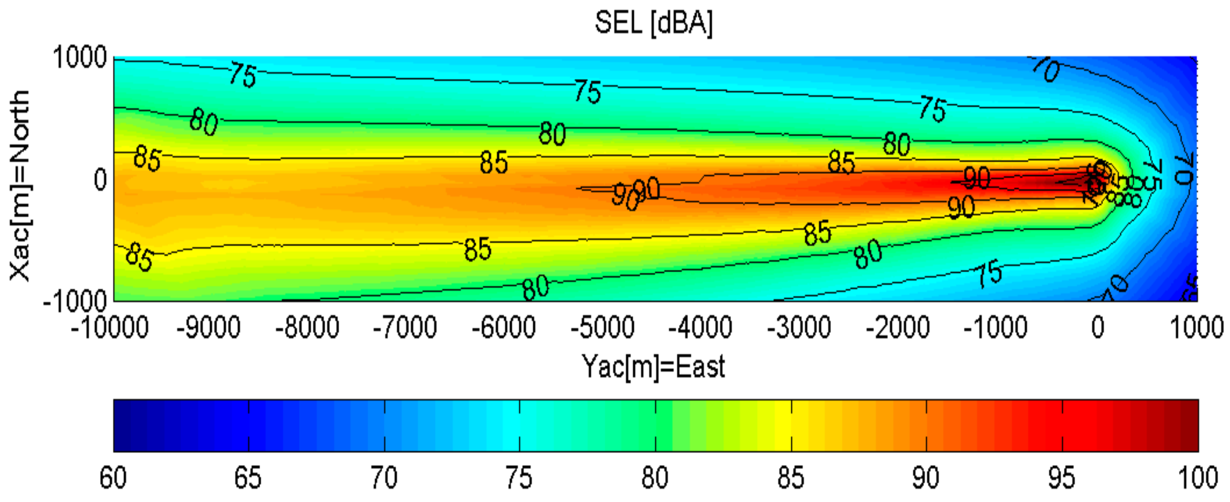

Figure 20: Noise footprint plot for TEM-R, reference approach (at 100% rotor rpm)

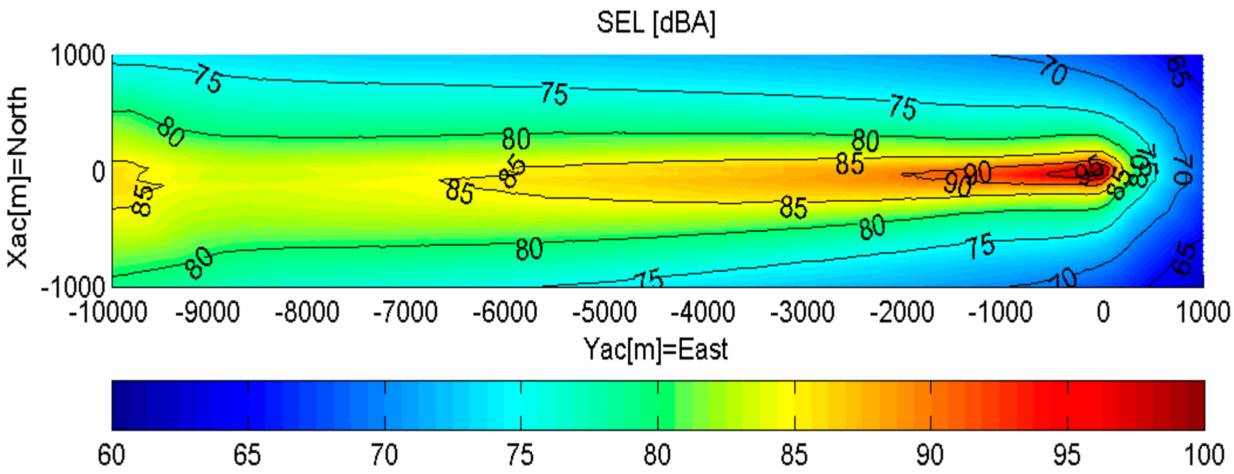

Figure 21: Noise footprint plot for TEM-C, reference approach (at 95% rotor rpm)

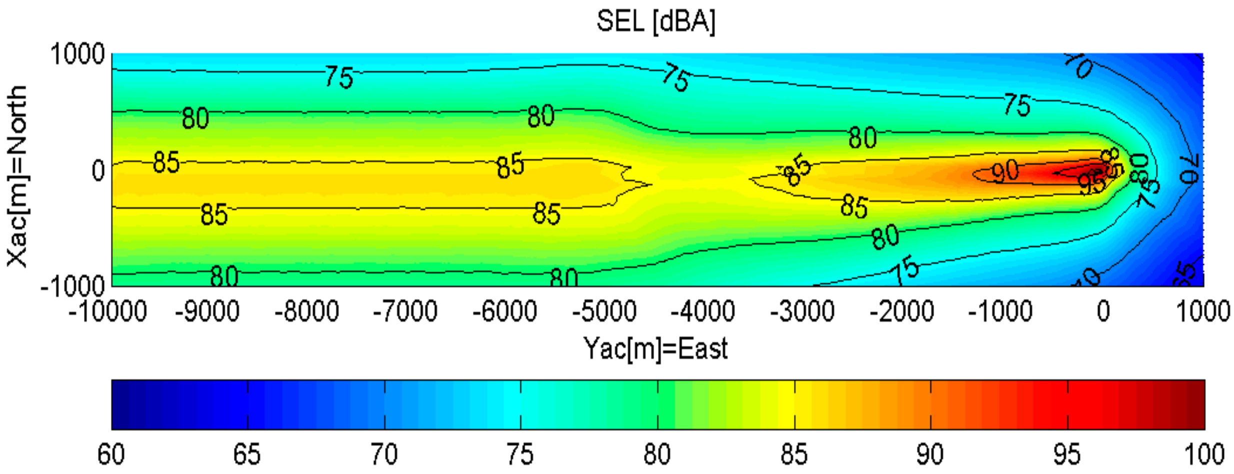

Figure 22: Noise footprint plot for TEM-C, LNP approach (at 95% rotor rpm)

Going from Fig. 20 to Fig. 21 there is a considerable reduction in noise levels, which is mainly attributable to the use of POB on TEM-C (which also facilitates a reduction in rotor rpm). Going from Fig. 21 to Fig. 22 the differences stem from the adoption of a steeper approach flight path angle during the LNP approach.

Finally, Table 13 provides the 90 SEL (dBA) iso-noise contour area reductions for the three combinations, showing that a reduction of up to 80% is achievable.

Table 13: TEM noise analysis for approach and landing phase, 90 SEL (dBA) iso-noise contour areas

Combination	Δ Area (%)
TEM-R, Reference Approach	0
TEM-C, Reference Approach	-75.4
TEM-C, LNP Approach	-79.9

10 Conclusions

Trade-off studies have been performed for three helicopter configurations with various implemented technologies. The analyses have been performed for default mission profiles as well as for more demanding mission profiles. The latter have been defined to (try to) maximize the potential benefits for specific technologies. The results of the trade-off studies show that the adoption of new technologies has a large potential of reducing important metrics like fuel burn, CO2 and NOx gas emissions, and noise footprints between Reference and Conceptual helicopter configurations. The reductions are consistent throughout, with larger benefits being possible for more demanding missions. Differences between the helicopter configurations are apparent, as indicated hereafter.

Single Engine Light (SEL)

Depending on the mission profile the potential reductions due to the incorporation of individual technologies range from zero up to:

- Fuel burn/CO2 11%
- NOx 54%

The potential reductions for all technologies combined amount up to:

- Fuel burn/CO2 21%
- NOx 70%

For HCE the potential reductions for all technologies combined amount up to:

- Fuel burn/CO2 55%
- NOx 66%

Adopting the LNP approach and landing on SEL-C reduces the 85 SEL (dBA) iso-noise footprint contour area during approach and landing by about 90% when compared to the SEL-R reference approach.

Twin Engine Light (TEL)

Depending on the mission profile the potential reductions due to the incorporation of individual technologies range from zero up to:

- Fuel burn/CO2 3%
- NOx 44%

The potential reductions for all technologies combined amount up to:

- Fuel burn/CO2 7%
- NOx 48%

Adopting the LNP approach and landing on TEL-C reduces the 85 SEL (dBA) iso-noise footprint contour area during approach and landing by more than 77% when compared to the TEL-R reference approach.

Twin Engine Medium (TEM)

Depending on the mission profile the potential reductions due to the incorporation of individual technologies range from zero up to:

- Fuel burn/CO2 7%
- NOx 50%

The potential reductions for all technologies combined amount up to:

- Fuel burn/CO2 11%
- NOx 59%

Adopting the LNP approach and landing on TEM-C reduces the 90 SEL (dBA) iso-noise footprint contour area during approach and landing by about 80% when compared to the TEM-R reference approach.

Remark

It is to be noted that the 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. Those values for fuel burn/CO2 are about 5% for SEL, 8.5% for TEL and 3% for TEM. Including those additional benefits brings the results closer to the GRC objective. With the range of innovative technologies that have been developed for the various rotorcraft platforms it is possible to come close to or even supersede the environmental targets that have been set for GRC.

11 Acknowledgements

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) for the Clean Sky Joint Technology Initiative under grant agreement n° CSJU-GAM-GRC-2008-001. The support of the European Commission and of the CleanSky Joint Undertaking (CSJU) is gratefully acknowledged.

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Appendix A Details regarding technologies and mission profiles

Table A.1: Details for technologies adopted on various helicopter classes

		Technology	Characteristics
SEL-C	GRC1	Passive Optimized Blades (POB)	performance and acoustic benefits
	GRC2	Drag reduction	rotor head, fuselage, skids
	GRC2	Dynamic air intake	reduced losses
	GRC3	Innovative electrical systems	efficient electrical generation, conversion and distribution; e.g. brushless starter generator
	GRC4	High Compression Engine	reduced fuel burn and NOx emission (only applied to SEL-C)
	GRC6	Structural weight saving	weight reduction
	SAGE5	New engine	reduced fuel burn and NOx emission
TEL-C	GRC1	Passive Optimized Blades (POB)	performance and acoustic benefits
	GRC2	Drag reduction	rotor head, fuselage, skids
	GRC2	Dynamic air intake	reduced losses
	GRC3	Innovative electrical systems	efficient electrical generation, conversion and distribution; electro-mechanical actuators
	GRC6	Structural weight saving	weight reduction
	SAGE5	New engine	reduced fuel burn and NOx emission
TEM-C	GRC1	Passive Optimized Blades (POB)	performance and acoustic benefits
	GRC1	Active Gurney Flap (AGF)	performance and acoustic benefits; facilitating rotor speed reduction
	GRC2	Drag reduction	rotor head, skids
	GRC2	Dynamic air intake	reduced losses
	GRC3	Innovative electrical systems	efficient electrical generation, conversion and distribution; electro-mechanical actuators, electric tail rotor drive
	GRC6	Structural weight saving	weight reduction
	SAGE5	New engine	reduced fuel burn and NOx emission

Table A.2: Details for selected mission profiles

	Mission type	Payload	Duration	Cruise speed	Cruise altitude
SEL	Default passenger mission	4 passengers	≈ ½ hrs	100-120 kts	1000-1500 ft, ISA
	Fire suppression	86 kg + 325 kg of water	≈ 2½ hrs	100-120 kts	580-1700 ft, ISA
	Long distance / high speed passenger transport	2 passengers	≈ 2 hrs	125 kts	2000 ft, ISA
TEL	Default EMS mission	580 kg (incl. 2 medical staff) + 3 patients	≈ ½ hrs	80-120 kts	1000-1500 ft, ISA
	Default police mission	300 kg + 2 police officers	≈ 1½ hrs	80-120 kts	1000-1500 ft, ISA
	Fire suppression	130 kg + 500 kg of water	≈ 2½ hrs	100-120 kts	580-1700 ft, ISA
	Long distance / high speed passenger transport	5 passengers	≈ 2 hrs	140 kts	2000 ft, ISA
TEM	Default fire suppression mission	172 kg + 650 kg of water	≈ 2½ hrs	100-120 kts	580-1700 ft, ISA
	Default SAR mission	312 kg (incl. 3 crew members) + 8 patients	≈ 2½ hrs	75-120 kts	200-2000 ft, ISA
	Long range passenger transport	1100 kg (incl. 10 passengers)	≈ 2½ hrs	135 kts	6500 ft, ISA+25°C

NLR

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